Concentrating Solar Power (CSP) Overview

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NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

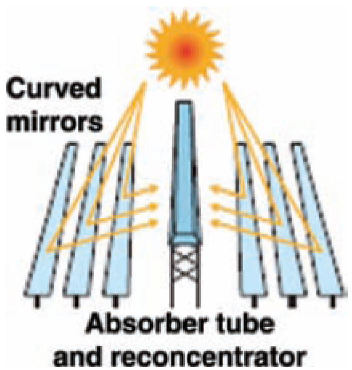
Discussion

- Technology Overview
  - CSP technologies
  - Hybridization with fossil energy
  - Value of thermal energy storage
  - Water Usage

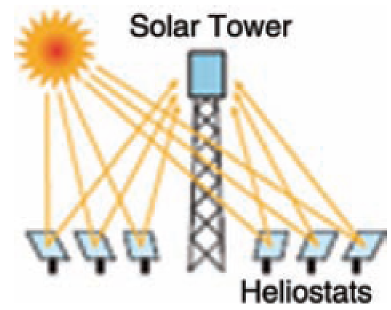
- U.S. and International Market Overview
- CSP Research and Development

CSP Technologies by Receiver Characteristics

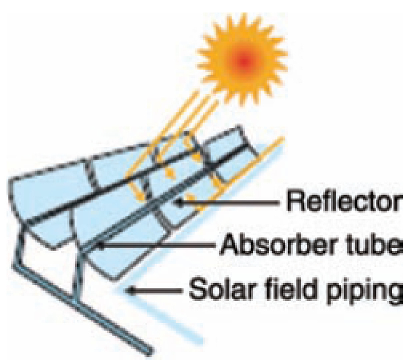
<table>
<tr><th>Focus type
Receiver</th><th>Line focus</th><th>Point focus</th></tr>
<tr>
<td>Fixed
Stationary receiver that remains mechanically independent of the concentrating system. The attainable working temperature depends of the concentration ratio.</td>
<td>Linear Fresnel



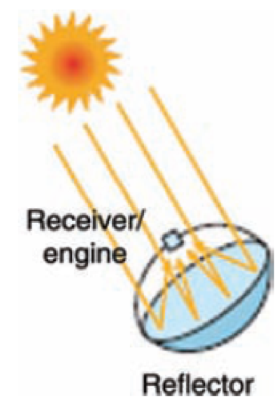
</td>
<td>Tower (central receiver systems)



</td>
</tr>
<tr>
<td>Tracking/aligned
The receiver moves together with the concentrating system. Mobile receivers collect more radiation energy than corresponding fixed receivers.</td>
<td>Parabolic Trough



</td>
<td>Parabolic Dish



</td>
</tr>
</table>

International Energy Agency, *Technology Roadmap: Concentrating Solar Power* (2010).

CSP Technologies by Market Sectors

CSP w/ Storage (Dispatchable)

- Parabolic trough
- Power tower
- Linear Fresnel

CSP w/o Storage (Non-Dispatchable)

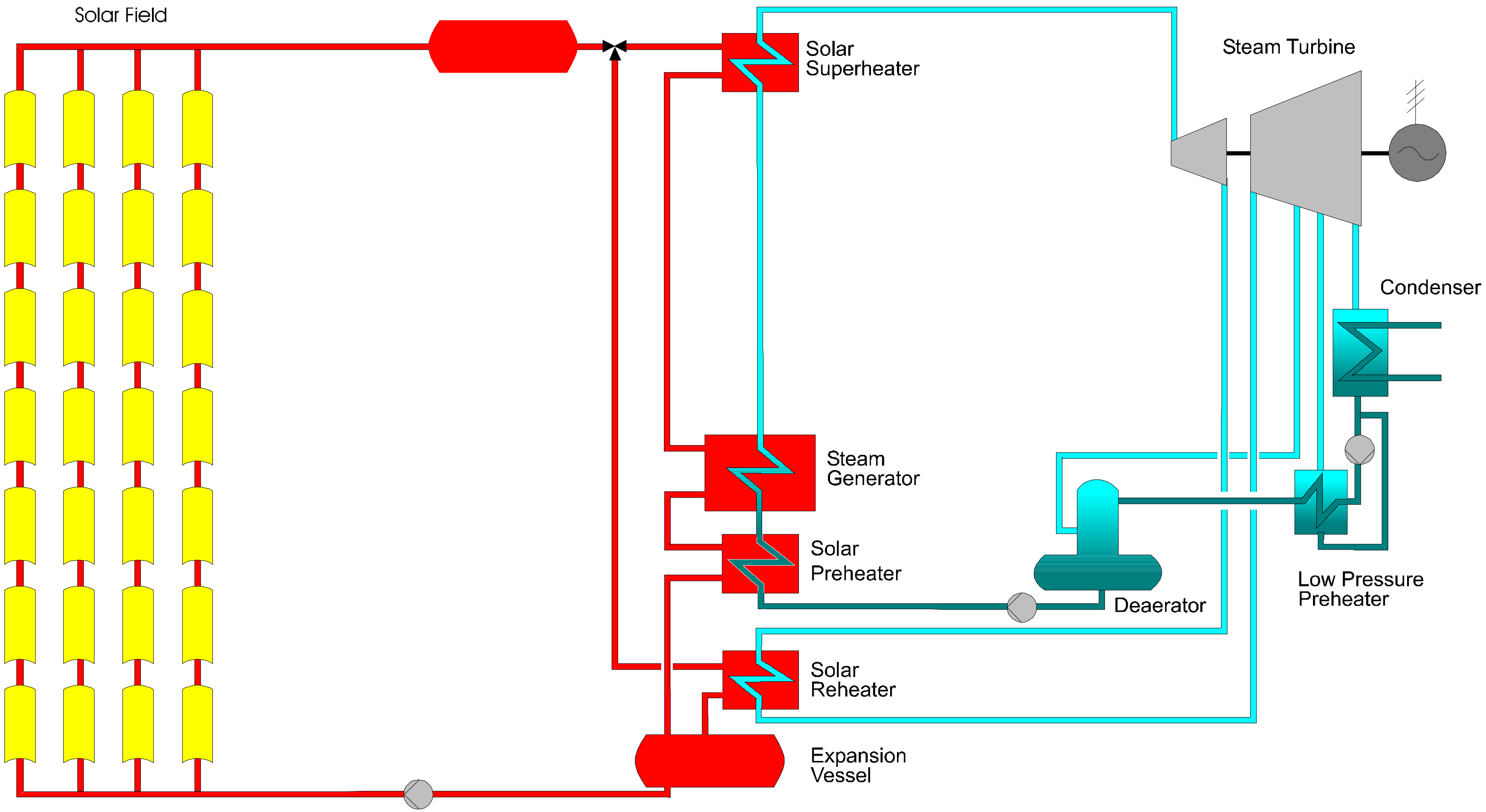
- Dish/Engine

Energy 101 CSP Video

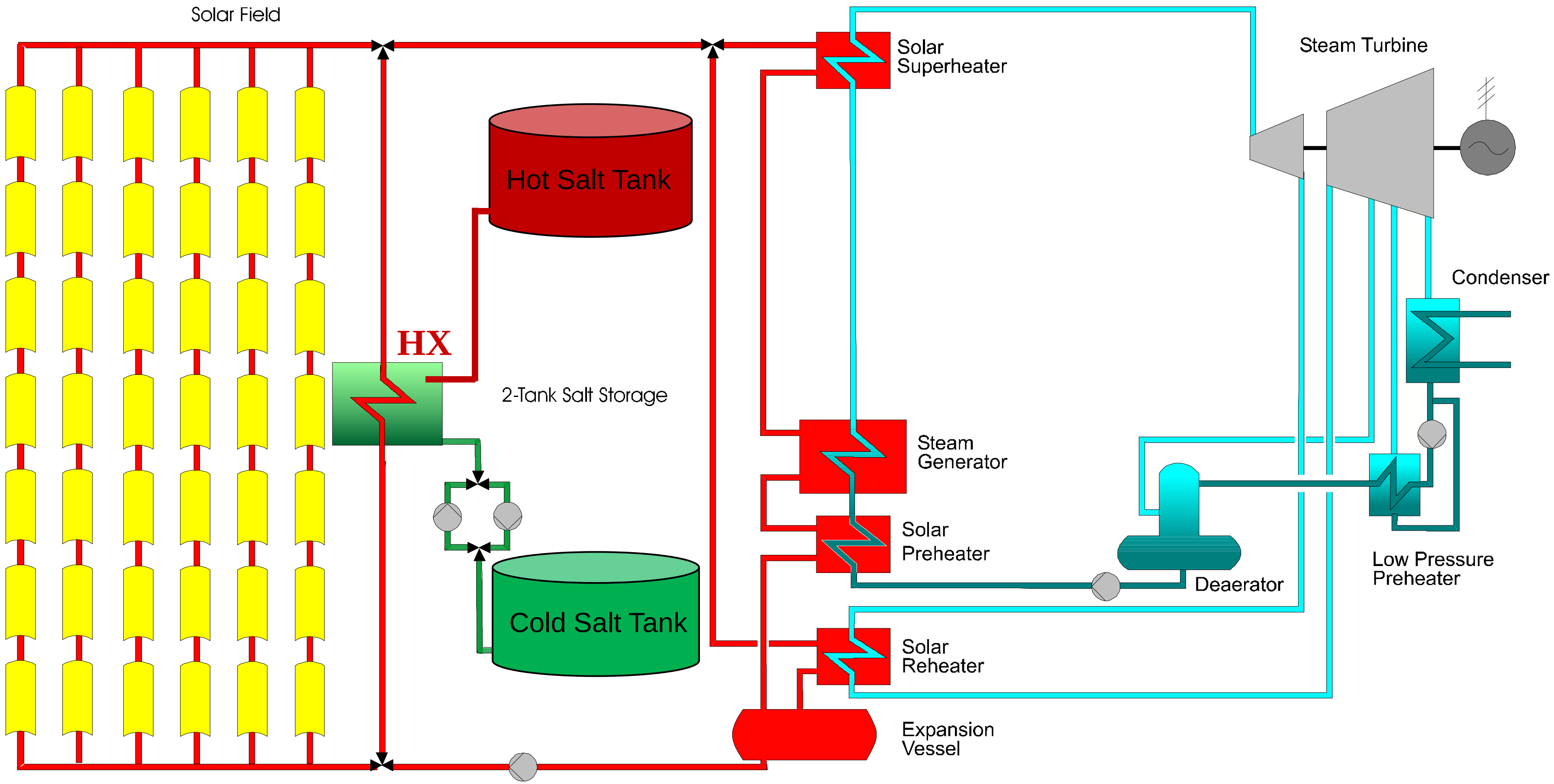
https://www.eeremultimedia.energy.gov/solar/videos/energy_101_concentrating_solar_power

Select “videos” under Browse by Media Types

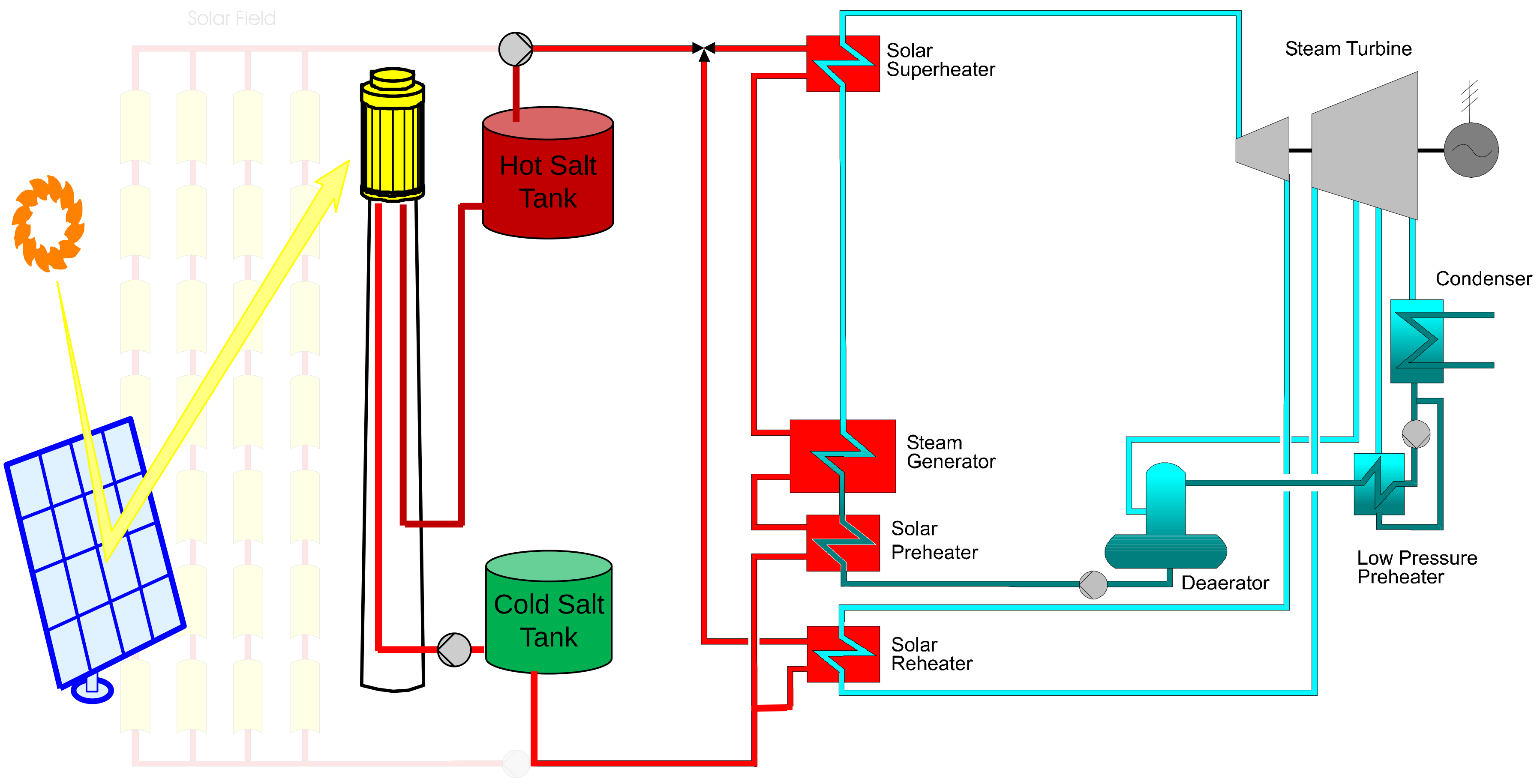
Parabolic Trough Power Plant without Thermal Storage



Parabolic Trough Power Plant
w/ 2-Tank Indirect Molten Salt Thermal Storage



Power Tower Plant
w/ 2-Tank direct Molten Salt Thermal Storage



Parabolic Trough

Design approaches:

- Oil HTF
  - All commercial plants to date
- Molten Salt HTF
  - Archimedes (pilot)
  - Abengoa (R&D)
- Direct Steam HTF
  - Abengoa (R&D)
  - Hittite Solar (R&D)
- Gas HTF
  - CIEMAT (R&D)

354 MW Luz Solar Electric Generating Systems (SEGS)
Nine Plants built 1984 - 1991

64 MWe Acciona Nevada Solar One
Solar Parabolic Trough Plant

50 MW AndaSol One and Two
Parabolic Trough Plant w/ 7-hr Storage, Spain

250 MW Solana Plant with 6 hrs Storage Under construction in Arizona

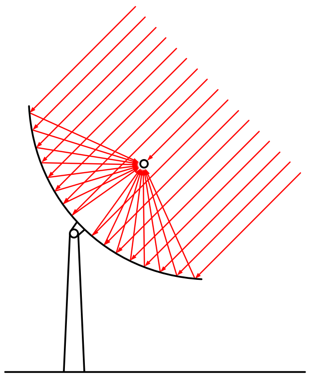
Linear Fresnel

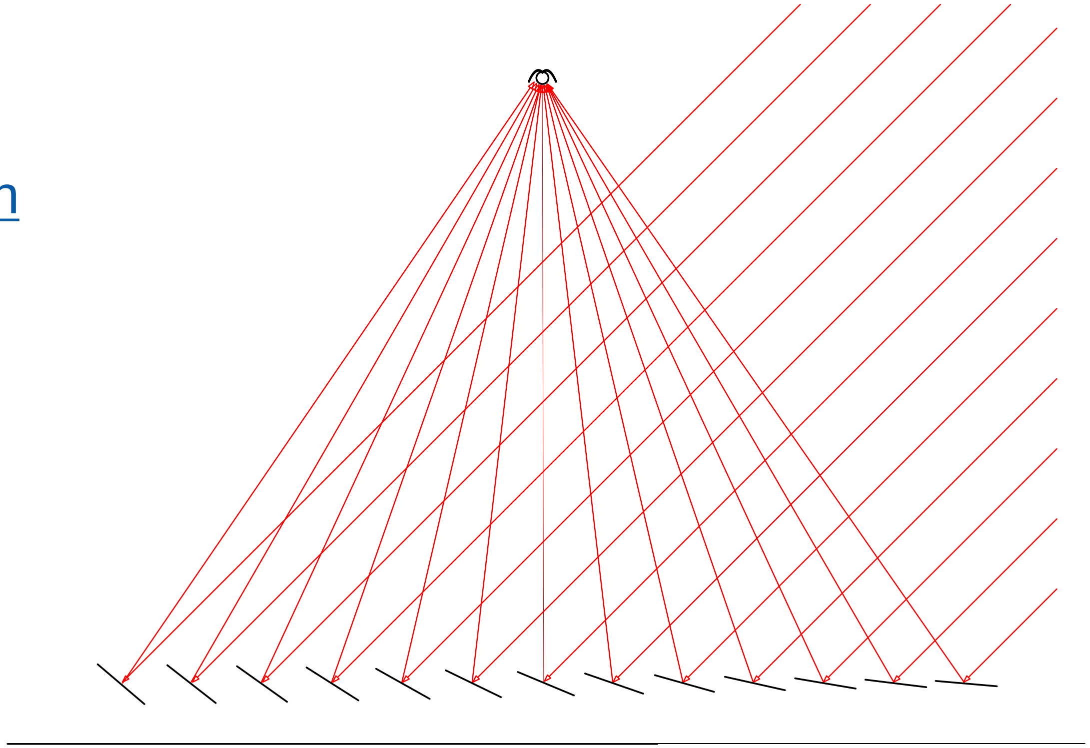
Areva Solar

Linear Fresnel Advantages

Linear Fresnel

Parabolic Trough





SkyFuel

Power Tower (Central Receiver)

Design approaches:

- Direct Steam HTF
  - Abengoa PS10/PS20
  - BrightSource (Ivanpah)
  - eSolar (pilot)
- Molten Salt HTF
  - Solar Two (pilot)
  - Torresol (Gemasolar)
  - SolarReserve (Crescent Dunes)
- Air HTF
  - Jülich (pilot)
  - Solugas (R&D)

Power Towers CSP Video

https://www.eeremultimedia.energy.gov/solar/videos/concentrating_solar_power_power_towers

Select “videos” under Browse by Media Types

Abengoa PS10 and PS 20
Seville, Spain

Torresol Energy 20 MW Gemasolar
Seville, Spain

Power Towers under Construction: BrightSource 392 MW Ivanpah, California

Power Towers under Construction: BrightSource 392 MW Ivanpah, California

Environmental measures:
Solar field is not graded
Air-cooled condenser reduces water consumption by over 90%

Power Towers under Construction: SolarReserve 110 MWe Crescent Dunes, Nevada

Fast Facts:

- 10 hours of thermal energy storage
- 195-m tall tower
- 600 construction jobs; 45 permanent jobs
- 1600-acre site
- Hybrid cooling

Looking down at the storage tank foundations

Dish Systems

Dish/Engine:
pilot-scale deployments

Tessera Solar 1 MW demo plant outside Phoenix

Concentrating PV: Commercial and pilot-scale deployments

- Modular (3-25kW)
- Highest solar-to-electric efficiency
- Low water use
- Capacity factors limited to <25% due to lack of storage. R&D exploring storage options.

Dish / Engine Systems

3 kW Infinia Dish Stirling systems
Villarobledo, Spain
(Infinia Corporation, USA)

Infinia's Powerdish IV

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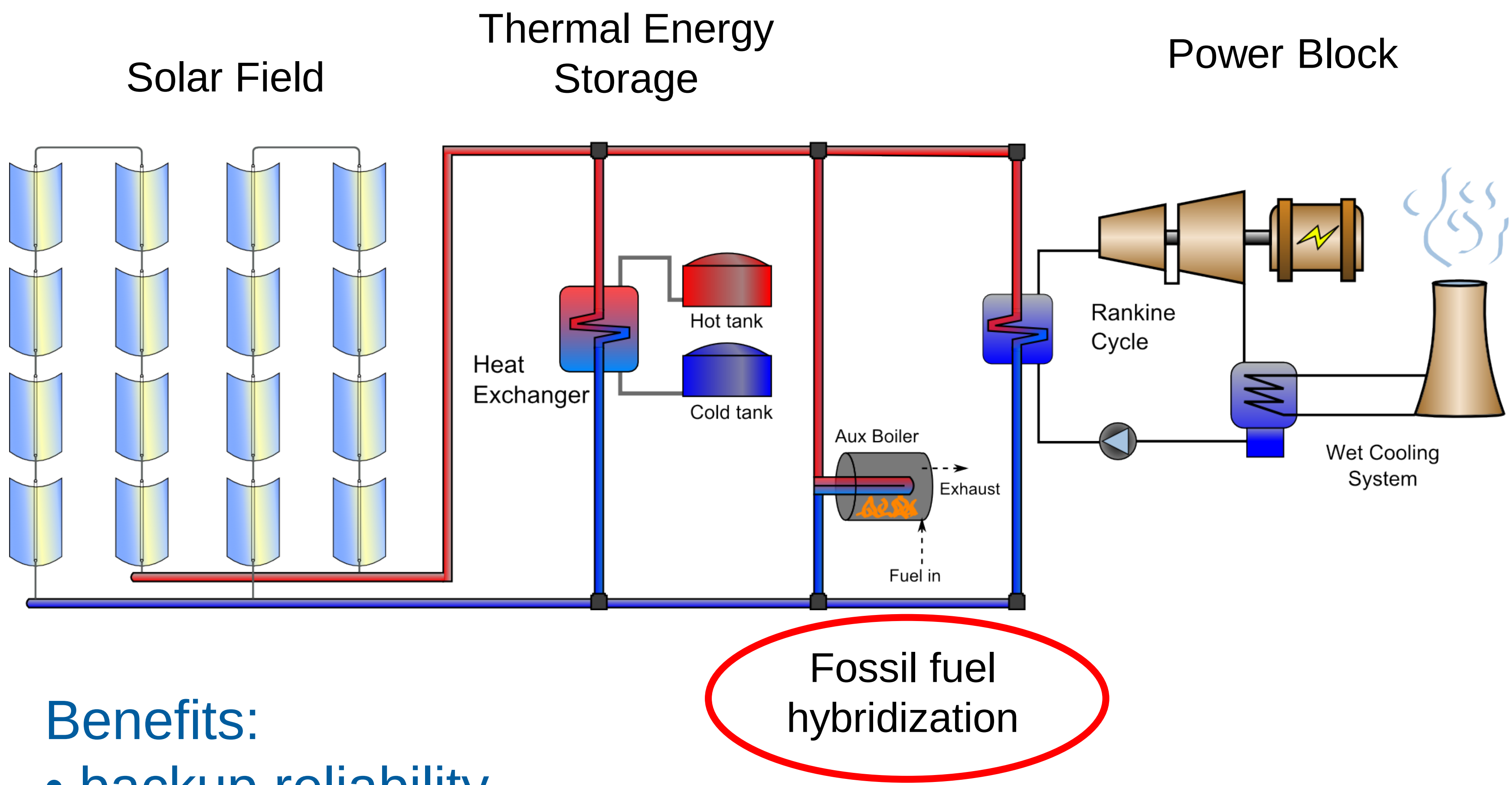
CSP Plants can Integrate with Fossil Systems

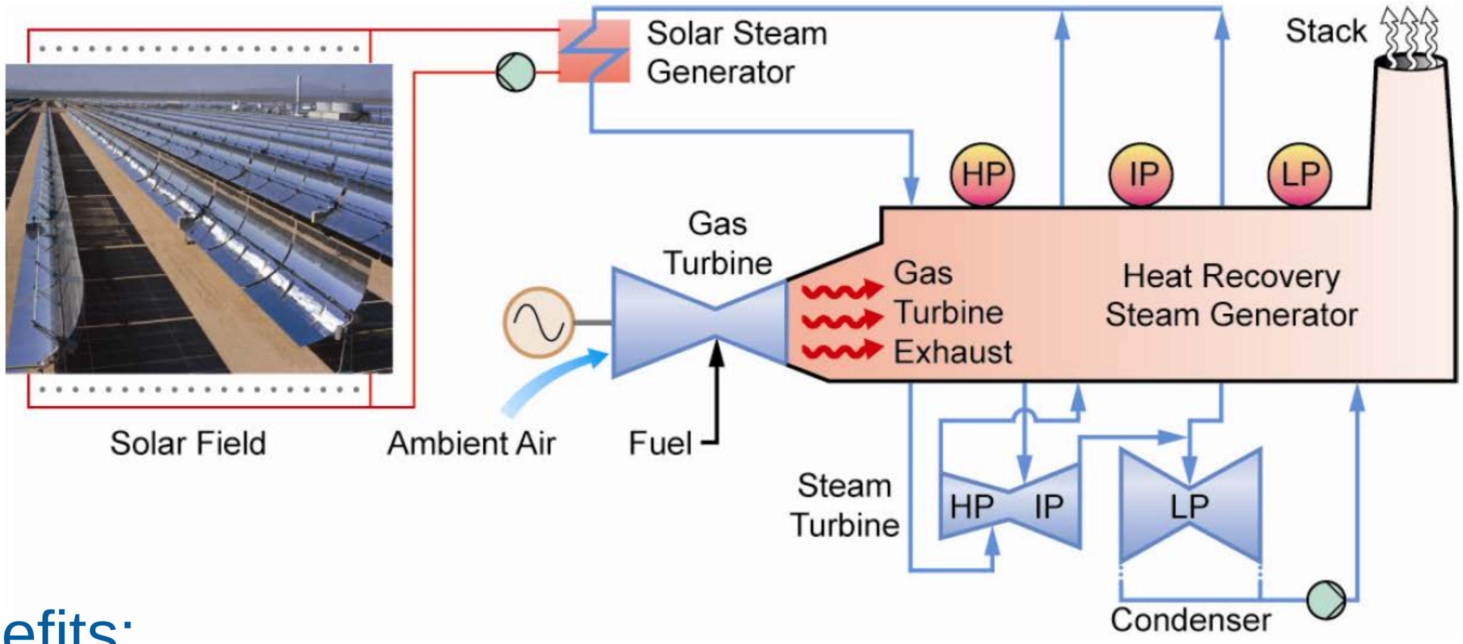


Benefits:

- backup reliability
- faster startup

Solar-Augment of Fossil Power Plants

CSP systems can supply steam to augment fossil-fired boilers.

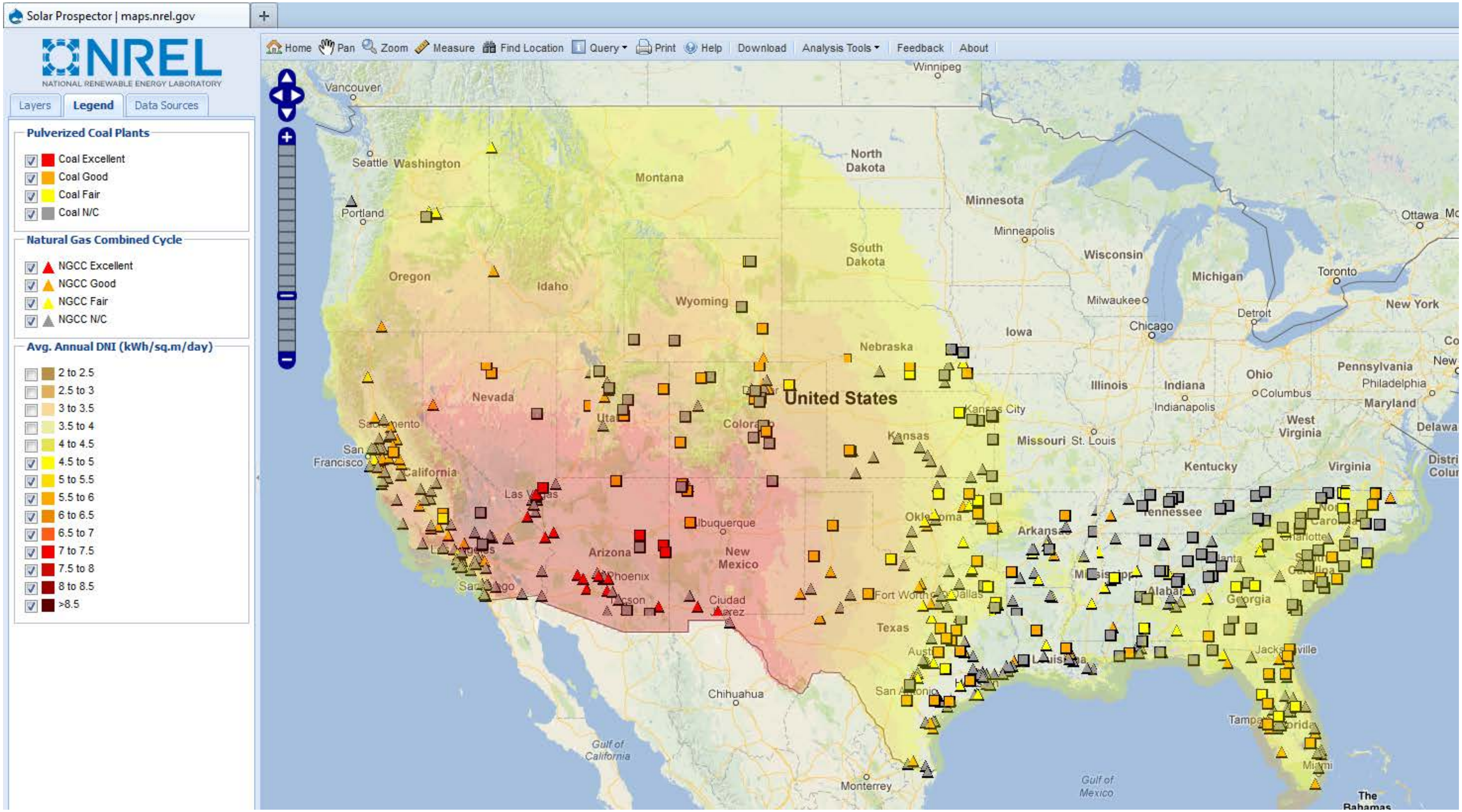


Benefits:

- shared power block, transmission access, staff
- good solar-to-electric efficiency

Graphic: EPRI

Solar-Augment Potential in the U.S. is >10 GW



http://maps.nrel.gov/prospector

75 MW Solar-Augment Plant in Florida

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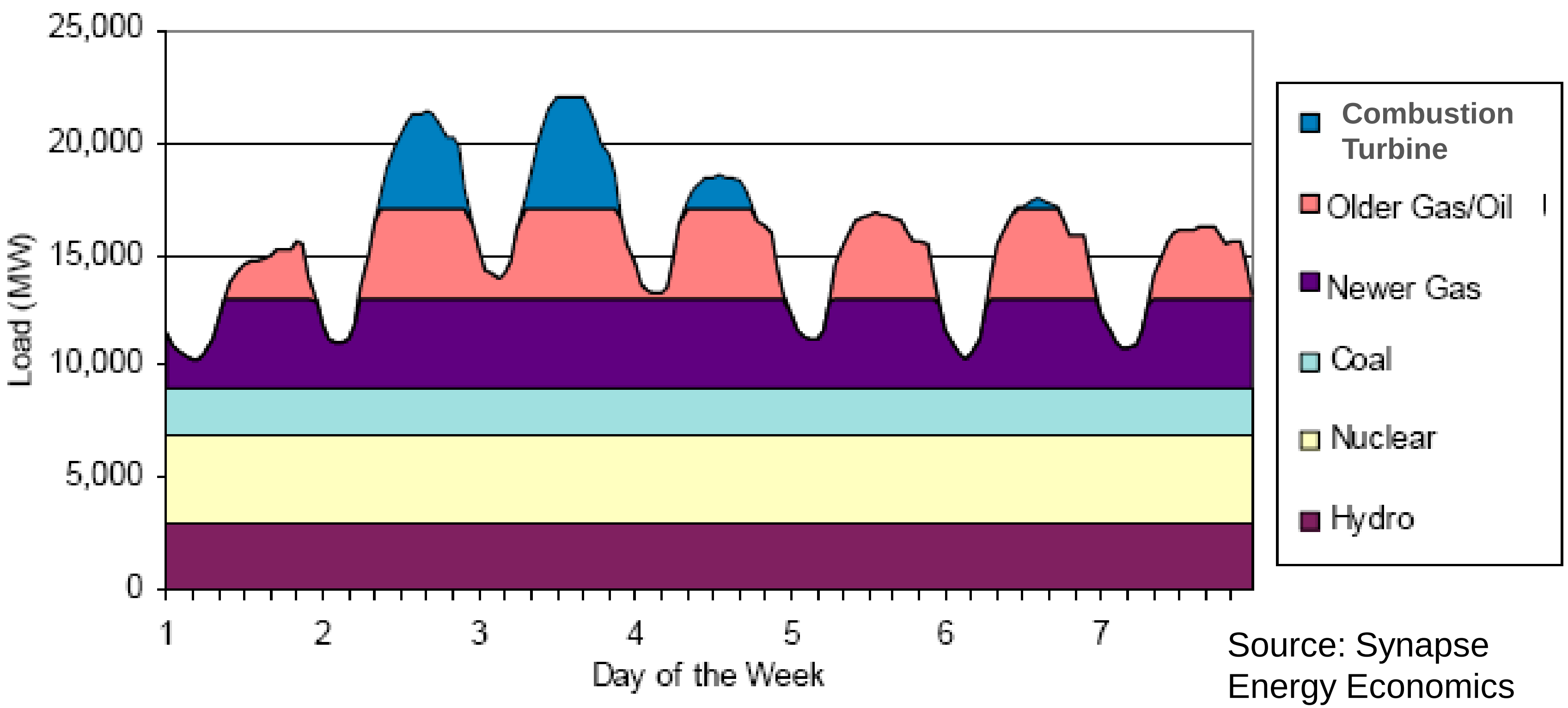
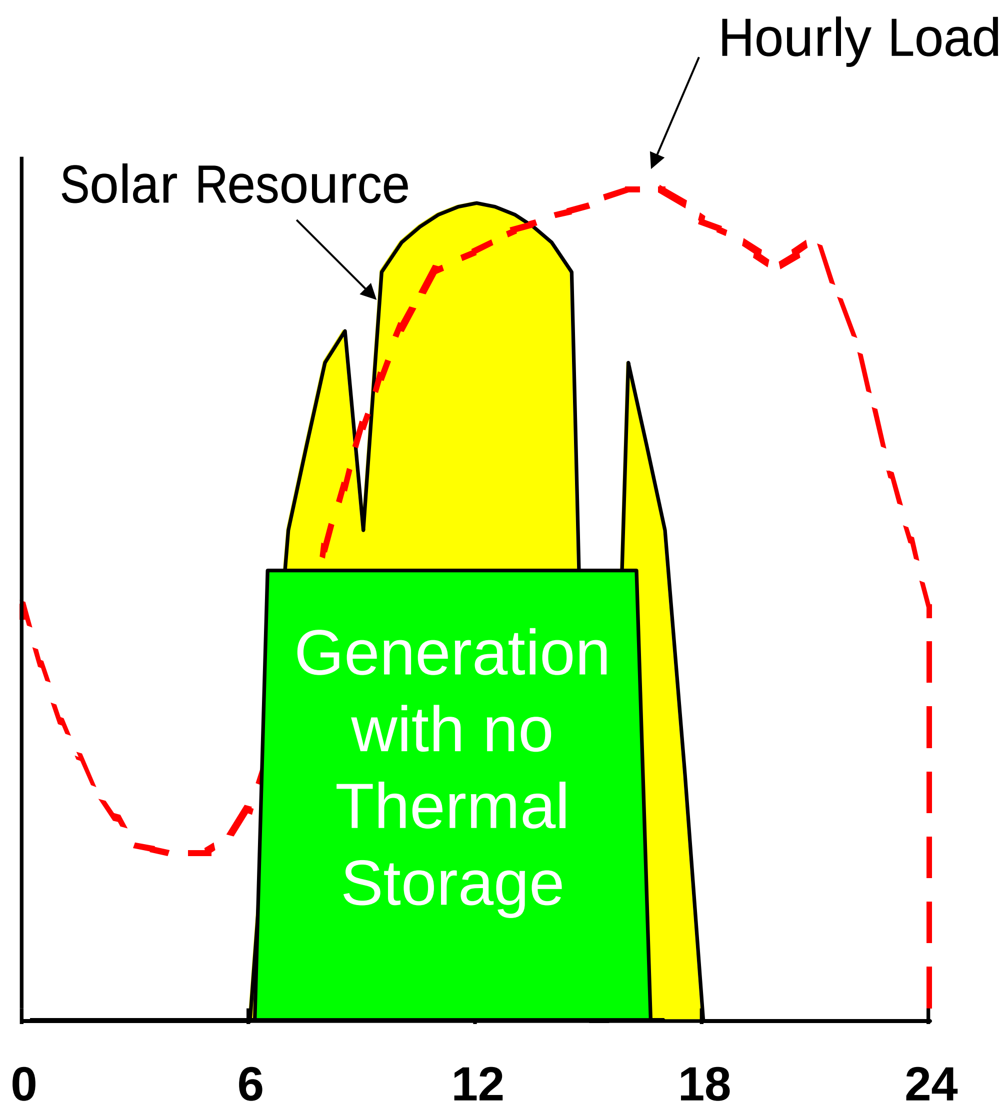
Electric Grid 101: Load Varies Daily



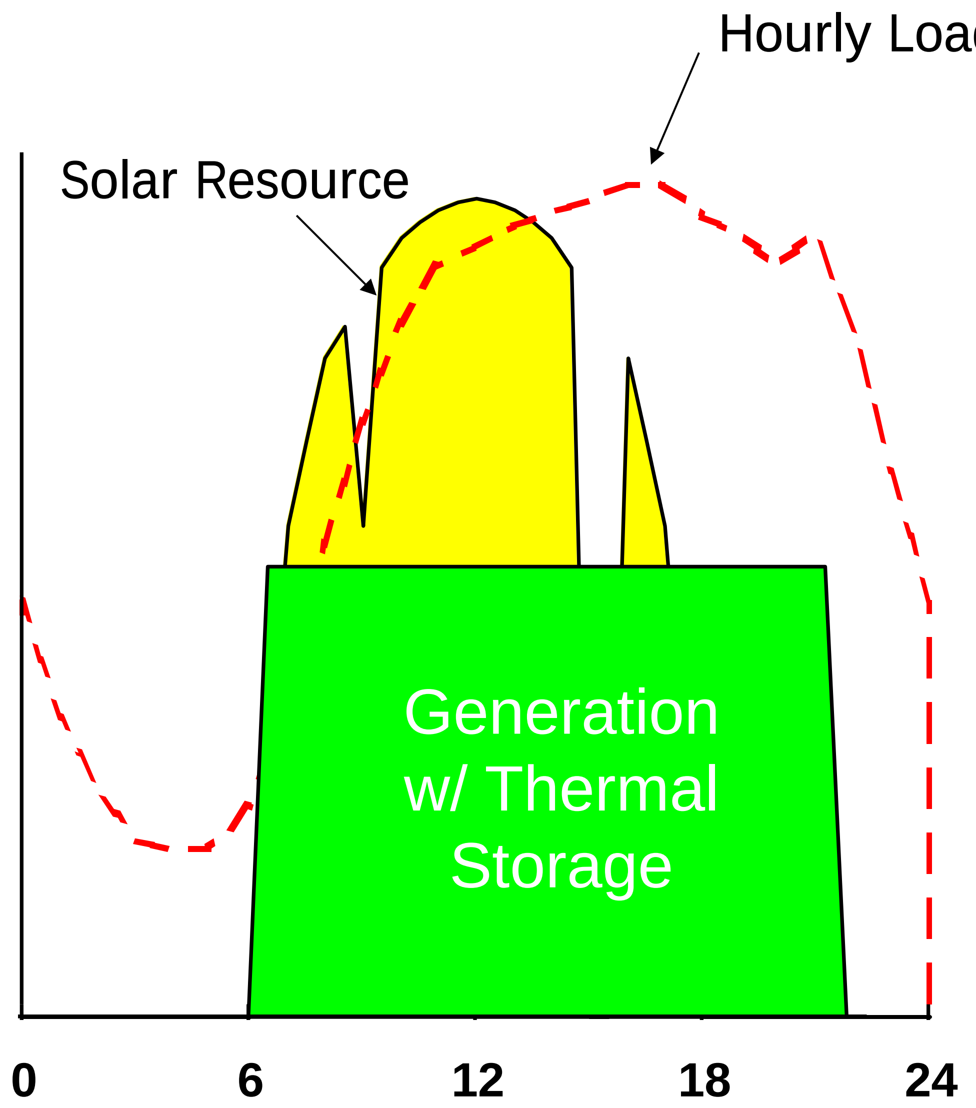
Source: Synapse Energy Economics

Operators strive to meet load with available resources at lowest cost.

CSP with Thermal Energy Storage
Meets Utility Demands for Power



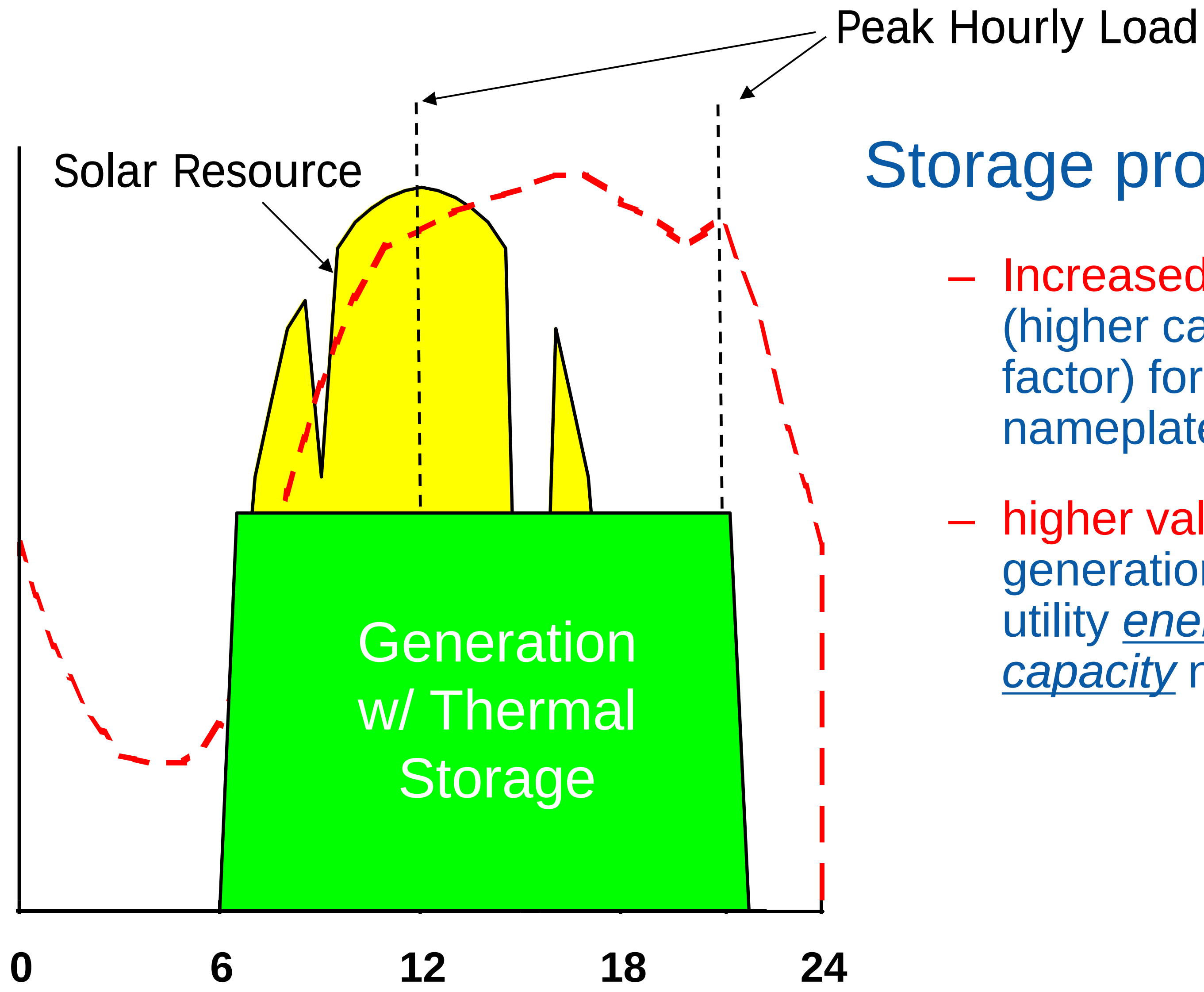
CSP with Thermal Energy Storage
Meets Utility Demands for Power



Storage provides:

- Increased generation (higher capacity factor) for given nameplate capacity

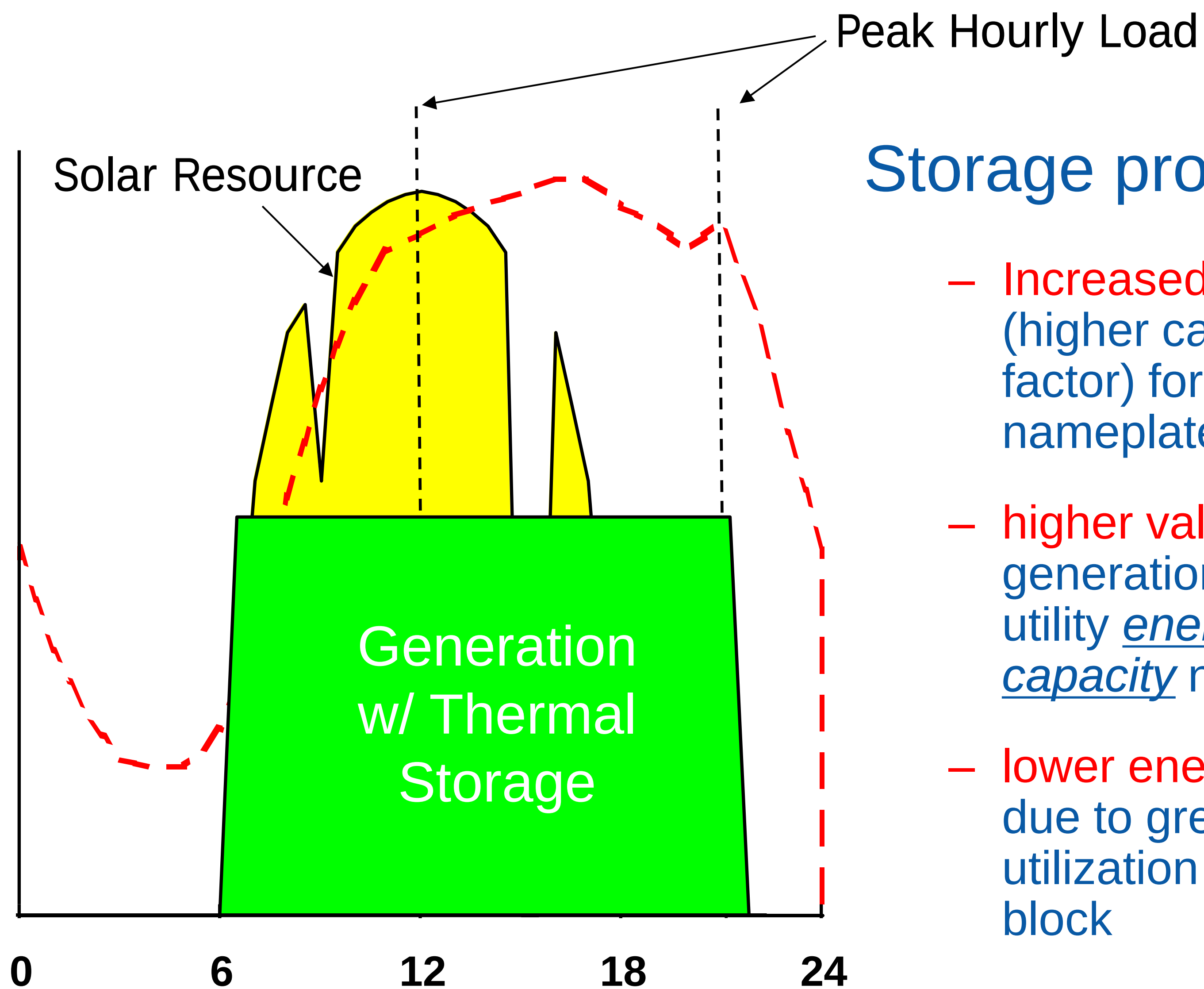
CSP with Thermal Energy Storage
Meets Utility Demands for Power



Storage provides:

- Increased generation (higher capacity factor) for given nameplate capacity
- higher value because generation can match utility *energy and capacity* needs

CSP with Thermal Energy Storage
Meets Utility Demands for Power



Storage provides:

- Increased generation (higher capacity factor) for given nameplate capacity
- higher value because generation can match utility *energy and capacity* needs
- lower energy costs due to greater utilization of power block

Value of Storage – Capacity and Energy

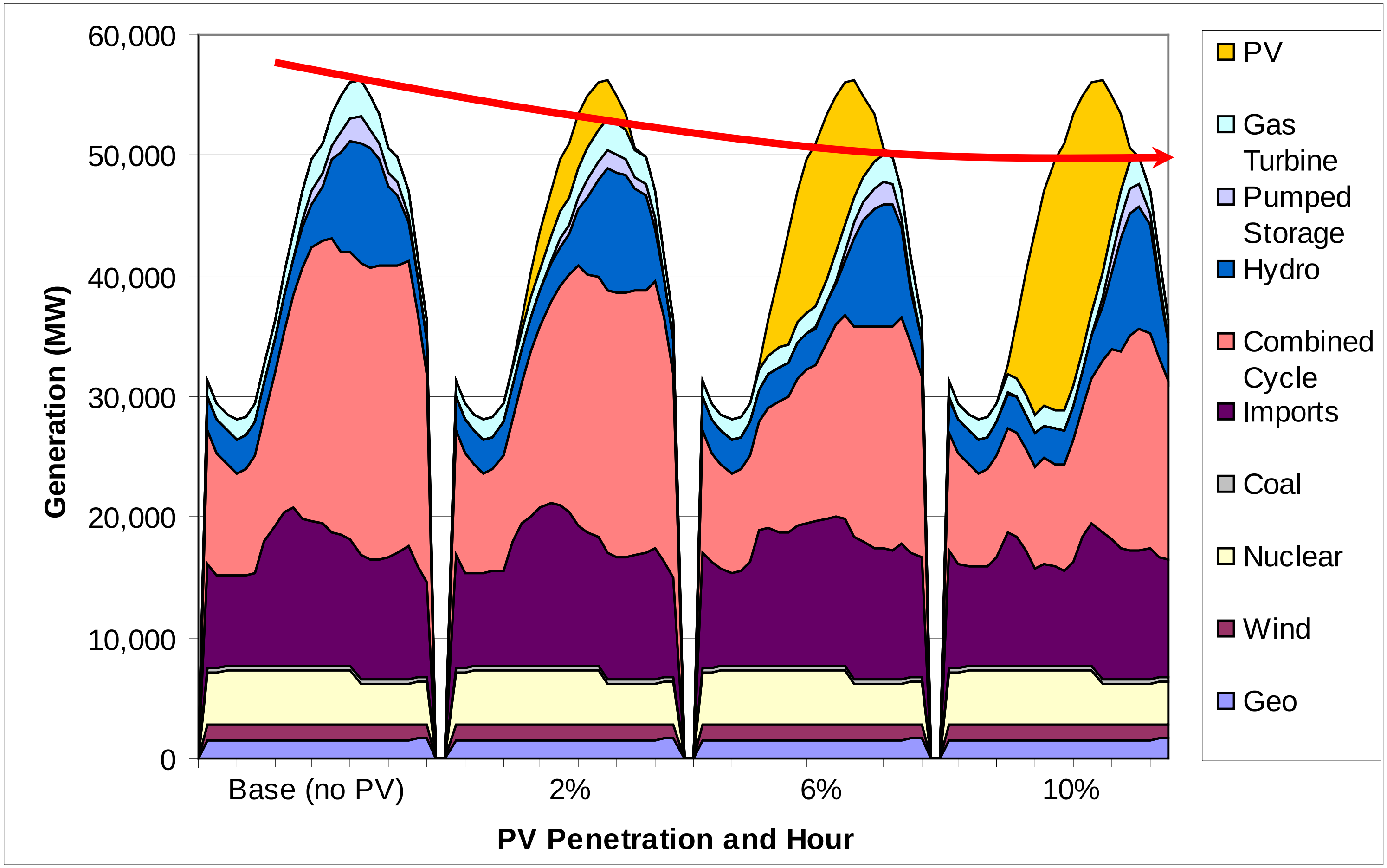
Capacity Value

- Additional value is given to a generating asset that provides firm generation during peak and minimizes loss of load probability
- Because loss of load probability is highest at peak load, generators whose output correlates positively with peak load receive the highest capacity value
- Not all kilowatt-hours are equal

Scenario	Wind	PV	CSP w storage
Low penetration (10% wind, 1% solar)	13.5%	35.0%	94.5%
Low penetration (20% wind, 3% solar)	12.8%	29.3%	94.8%
Low penetration (30% wind, 5% solar)	12.3%	27.7%	95.3%

Data from Western Wind & Solar Integration Study, NREL, May 2010

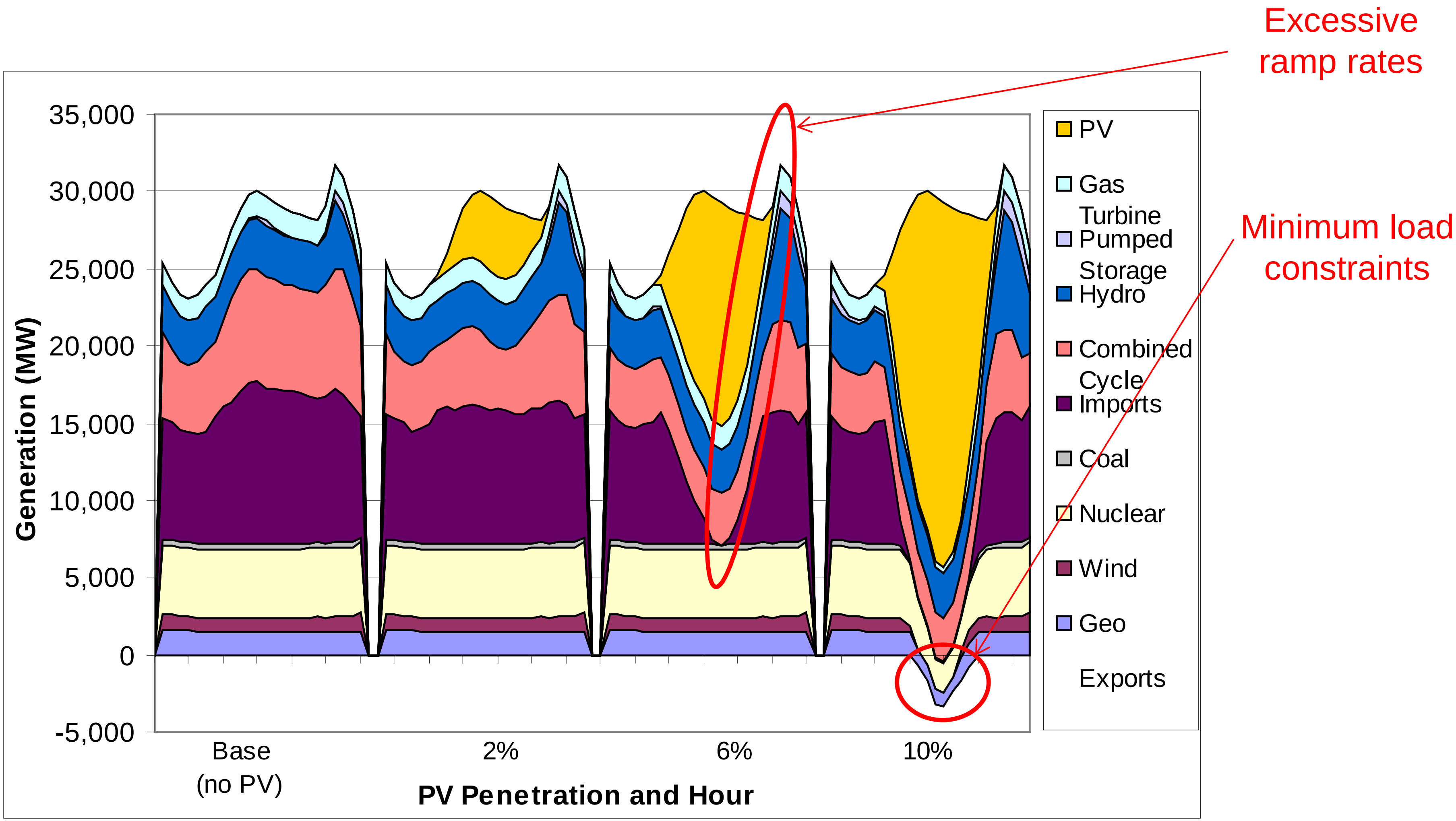
Simulated Dispatch in California for Summer Day for 0% to 10%PV Penetration



Decreased Capacity Value

Increased PV Penetration

Simulated Dispatch in California for Spring Day for 0% to 10%PV Penetration



Storage Gains Importance at High Solar Penetration

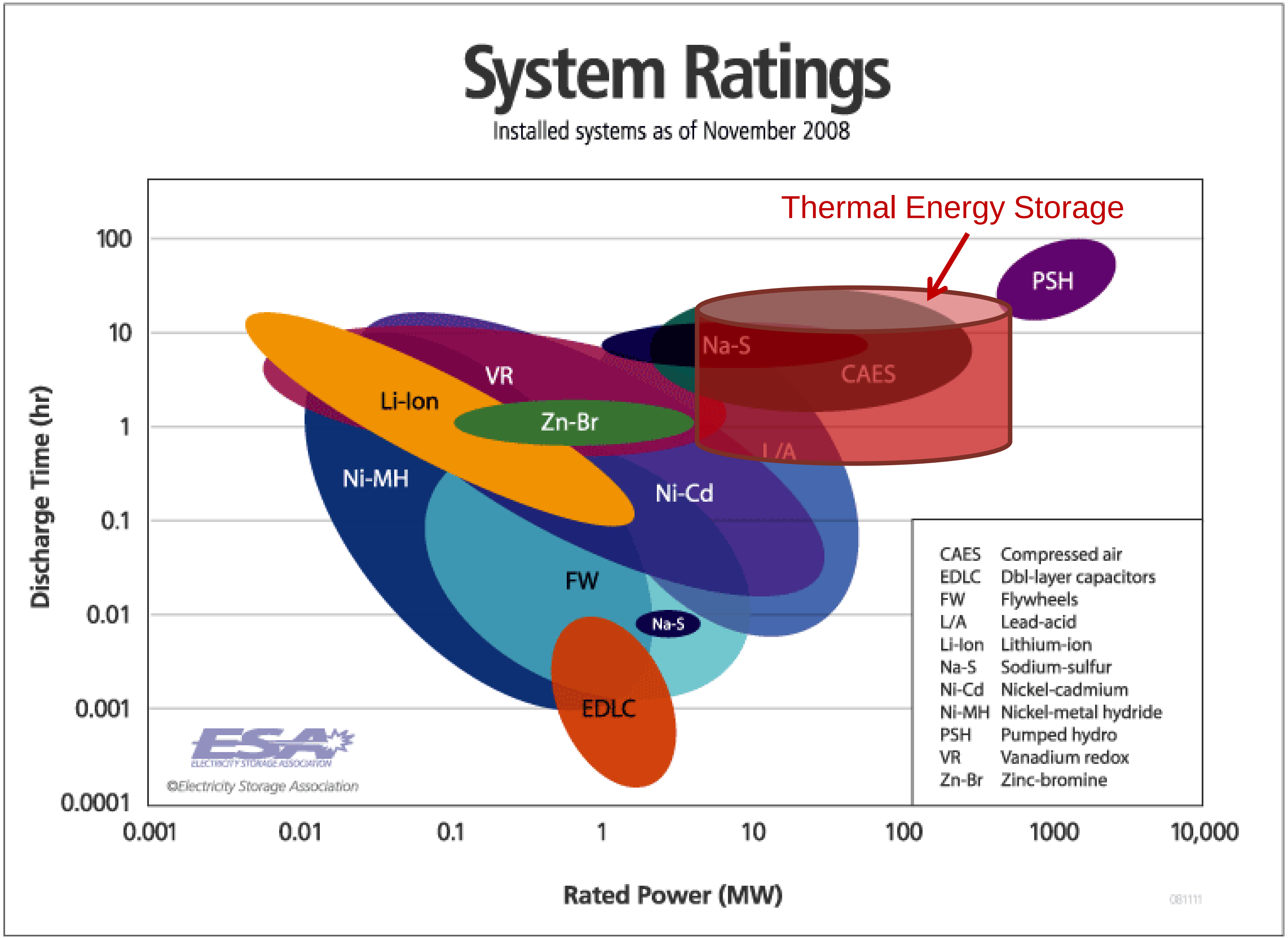
At 10%-15% solar penetration, the estimated *value* of CSP with storage is an additional 1.6-4.0 ¢/kWh relative to solar without storage.

Benefit offered by TES	Estimated Value
Energy shifting	0.5 -1.0 ¢/kWh
Higher capacity value	0.7 -2.0 ¢/kWh
Reduced curtailment	~0.3 ¢/kWh *
Lower reserve/integration costs	0.1-0.7 ¢/kWh

* Depends on PV cost. At 6 ¢/kWh, corresponds to ~0.3 ¢/kWh

Denholm 2011

Thermal Energy Storage: Massive Storage for Hours



Thermal Energy Storage: Efficiency and Low Cost

	Thermal Energy Storage	NaS Flow Battery*	Compressed Air Energy Storage*	Pumped Hydro*
Roundtrip energy efficiency (typical)	98%	75%	50%	75%
Energy Capacity (MWh)	1000	10	1000	10,000
Power Capacity (MW)	100+	5	100+	500
Storage Duration	hours	hours	days	days
Capital cost ($/kWh-e)	72 (towers) 210 (troughs)	750-1500	90-200	75-150
Service Life (yrs)	30	15	30	30

* Oudalov, Buehler, & Chartouni, ABB Corporate Research Center, "Utility Scale Applications of Energy Storage," IEEE Energy, 2030, Atlanta, GA, November 2008.

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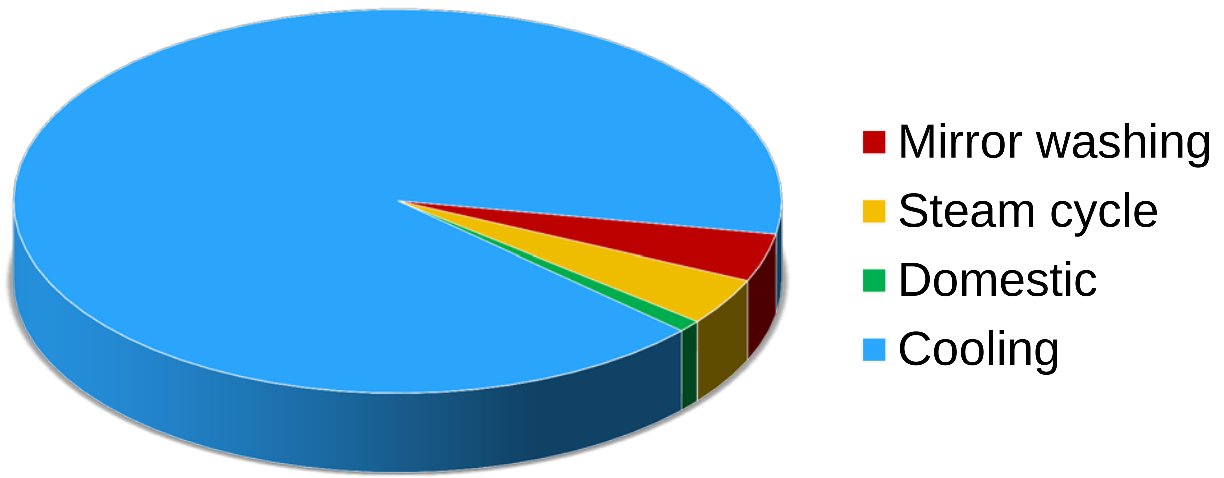
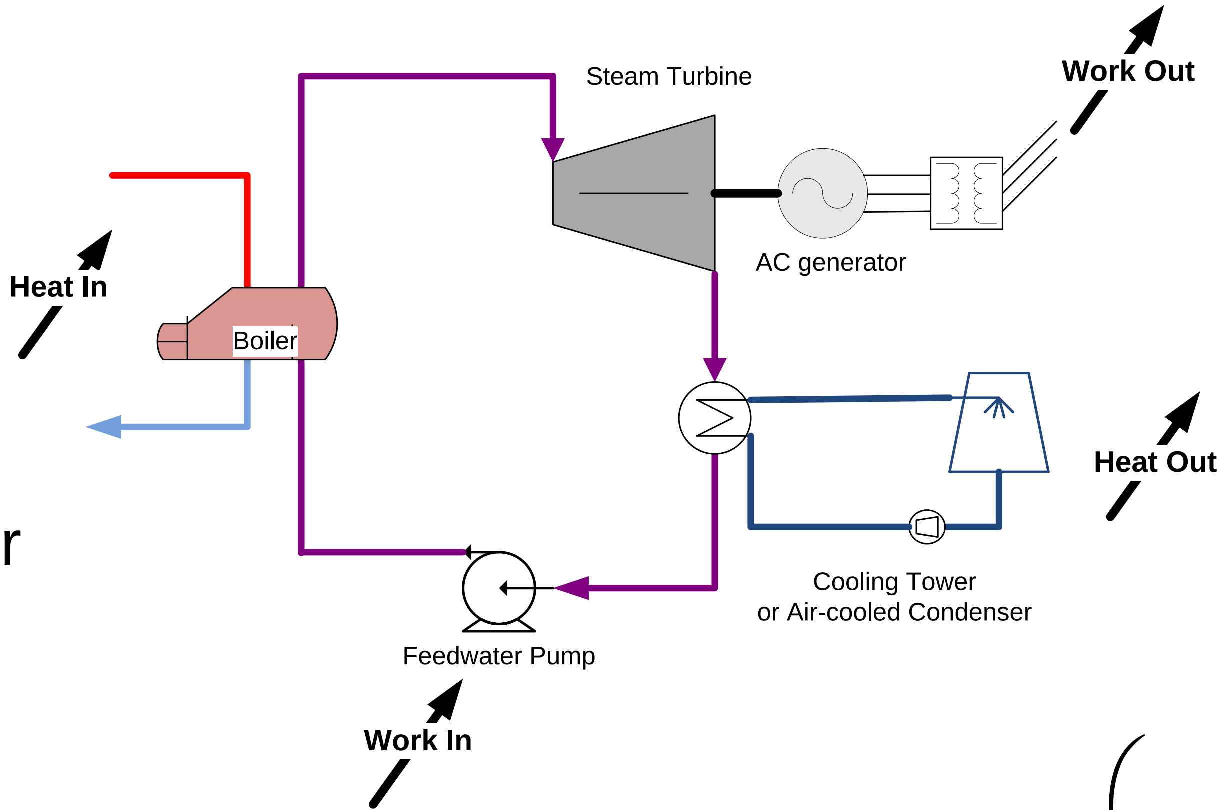
Water Usage at CSP Plants

- Mirror washing
- Steam cycle maintenance
- Staff (domestic)
- Power cycle cooling



All Thermoelectric Power Systems Need Cooling

Coal
Gas
Oil
CSP
Nuclear

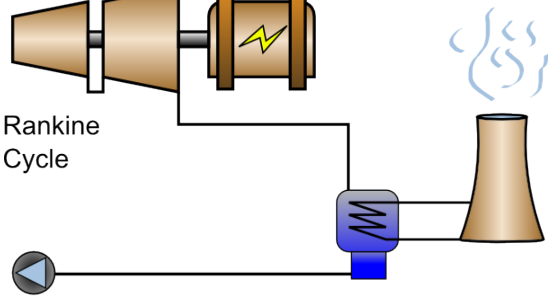


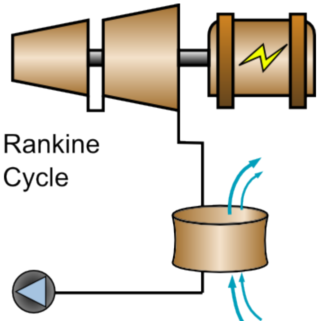
$$\text{Efficiency} \propto \left(1 - \frac{T_{cooling}}{T_{heatsource}}\right)$$

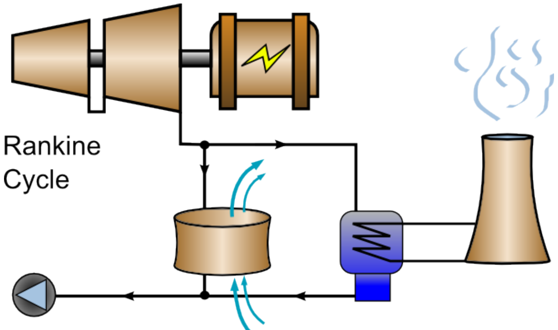
Primary Cooling Options

1. Wet cooling | 2. Dry cooling | 3. Hybrid cooling

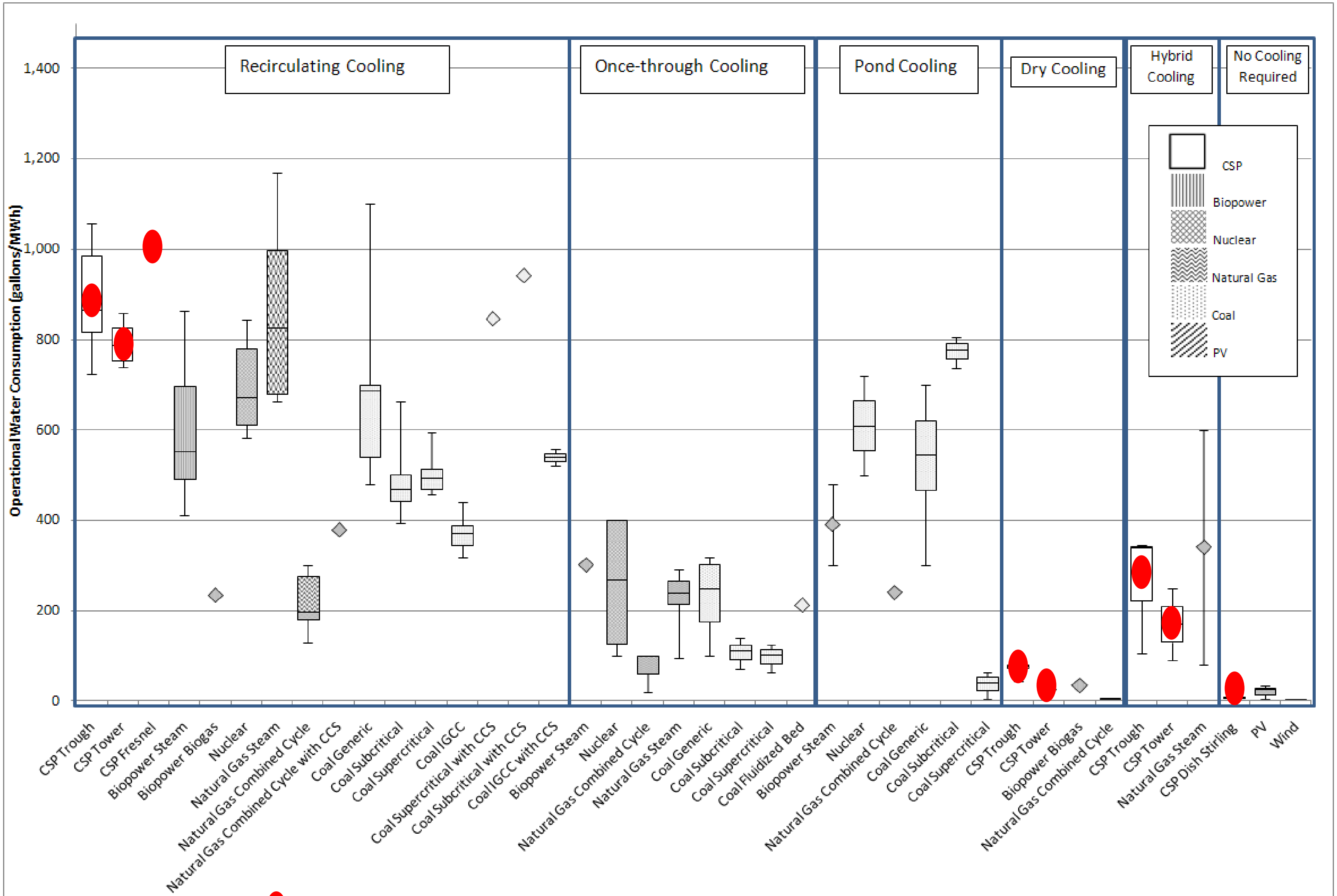
+







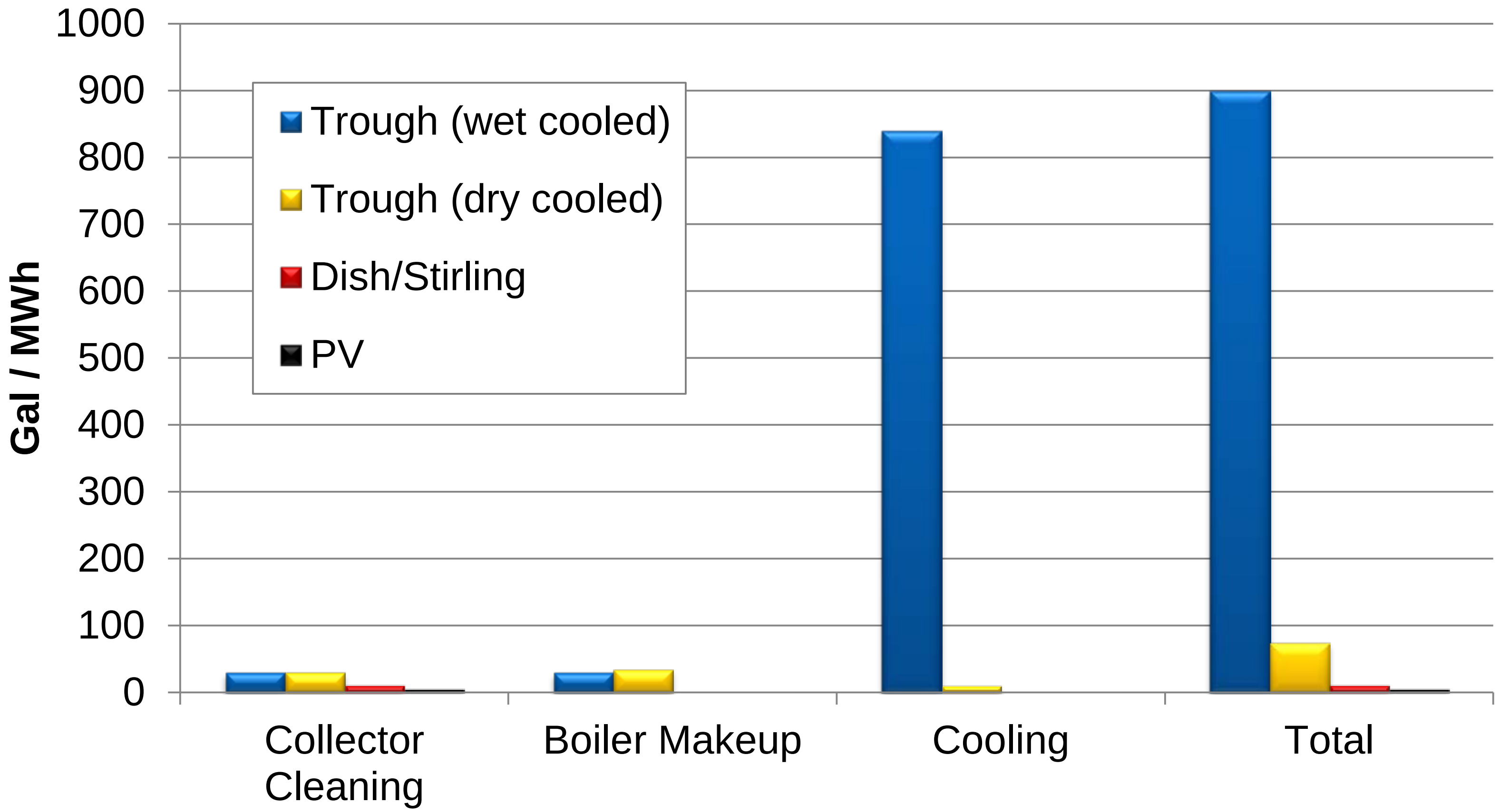
Comparison of Water Consumption Rates



= CSP technologies

Source: Macknick *et al.*, 2011

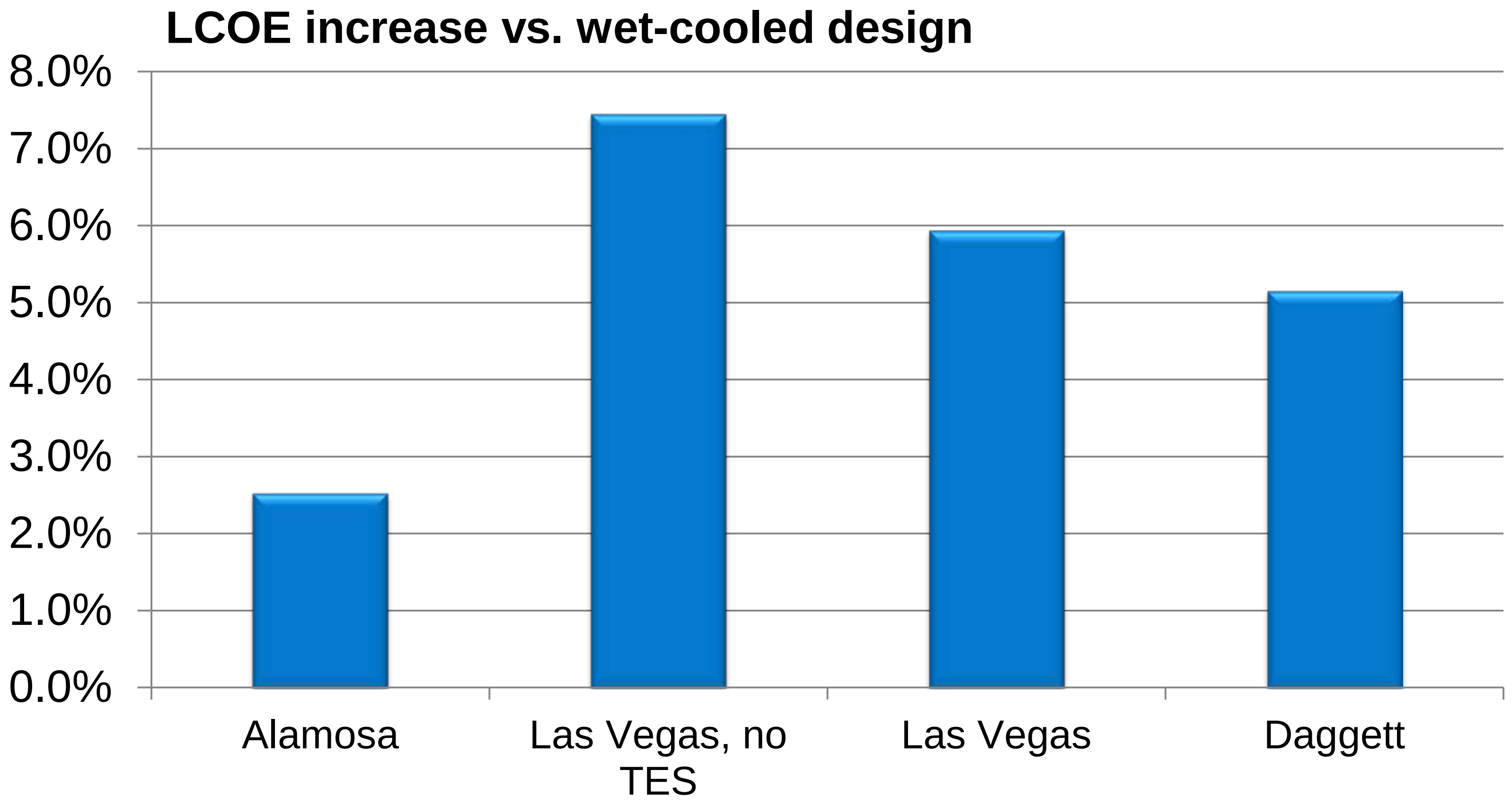
Water Usage of Solar Technologies



Values representative; specific usage varies by location, plant design and washing frequency.

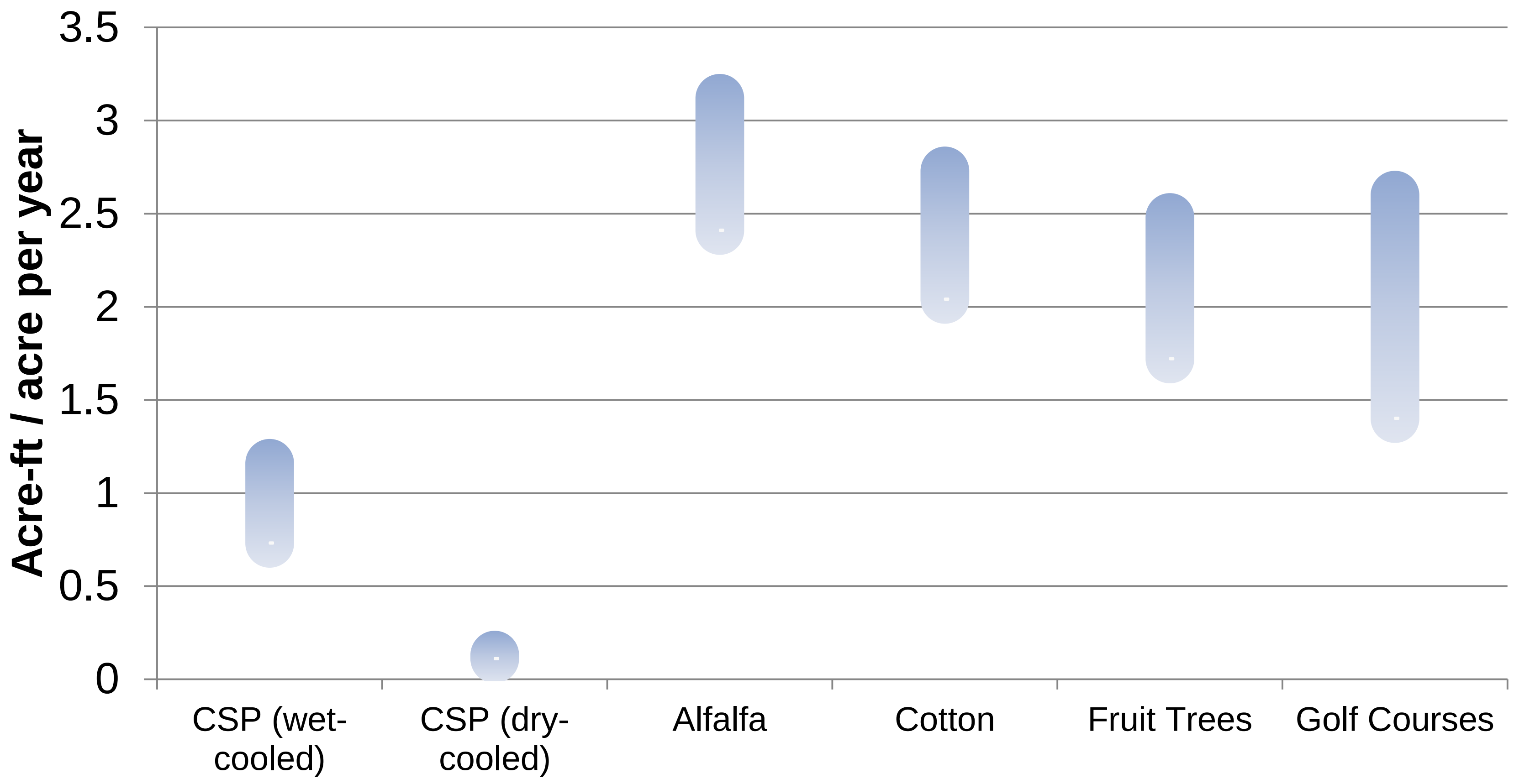
Dry Cooling Increases LCOE by 2.5% to 7.5%

Impact depends on location and technology. Data shown for parabolic troughs.



NREL/TP-5500-49468, December 2010

Water Use per Land Area



Sources:
CSP: Reducing Water Consumption of CSP Electricity Generation, Report to Congress 2009.
Crops: Blaney, Monthly Consumptive use of Water by Irrigated Crops & Natural Vegetation, 1957.
Golf : Watson et al., The Economic Contributions of Colorado’s Golf Industry: Environmental Aspects.

Solar Technology Summary Comparison

	Trough	Power Tower	Dish / Engine	PV
Typical Operating Temp	390ºC	565ºC	800ºC	ambient
Utility scale (>50 MW)	✓	✓	✓	✓
Distributed (<10MW)			✓	✓
Energy Storage	✓	✓		
Hybrid with fossil energy	✓	✓		
Water use (non-cooling)	💧💧	💧💧	💧	💧 to none
Water use for cooling	preferred	preferred		
Land Use (acre/MW)*	5-9	3-9	8-9	5-9
Land Slope	<3%	<5%	<5%	<5%
Technical maturity	medium	low	low	low to high

* Dependent on location and storage, values shown based on plants or announced projects

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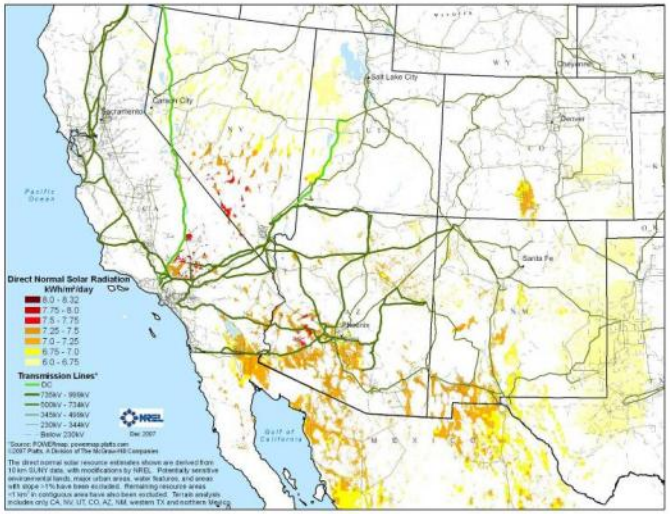
CSP Market Goals

– Competitive in southwest intermediate-load power markets
– less than 10¢/kWh real LCOE



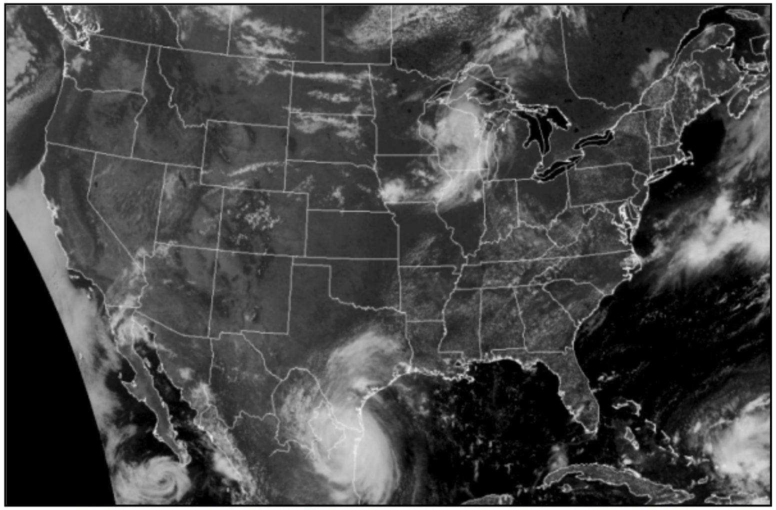
– Expand access to include carbon-constrained baseload power markets
– less than 8¢/kWh real LCOE

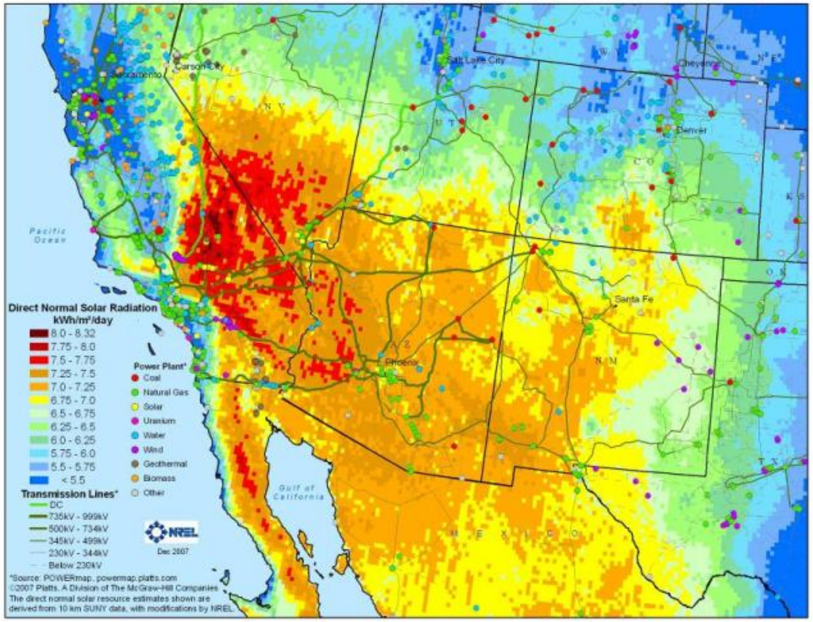
Screening Analysis for CSP Generation

Screening Approach

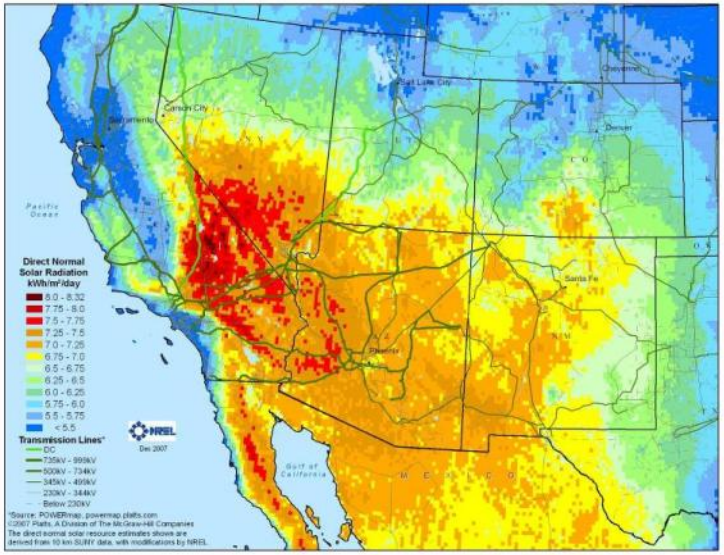
- Initial solar resource and screening analysis used to identify regions most economically favorable to construction of large-scale CSP systems

- Analysis used in conjunction with transmission and market analysis to identify favorable regions in the southwest

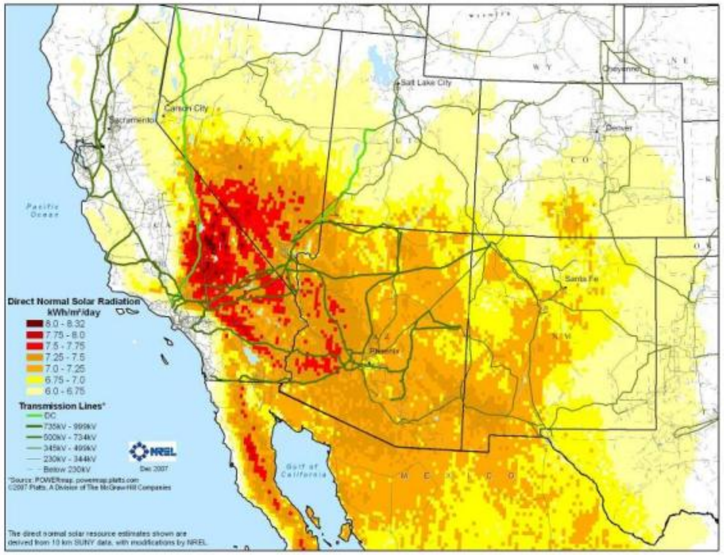




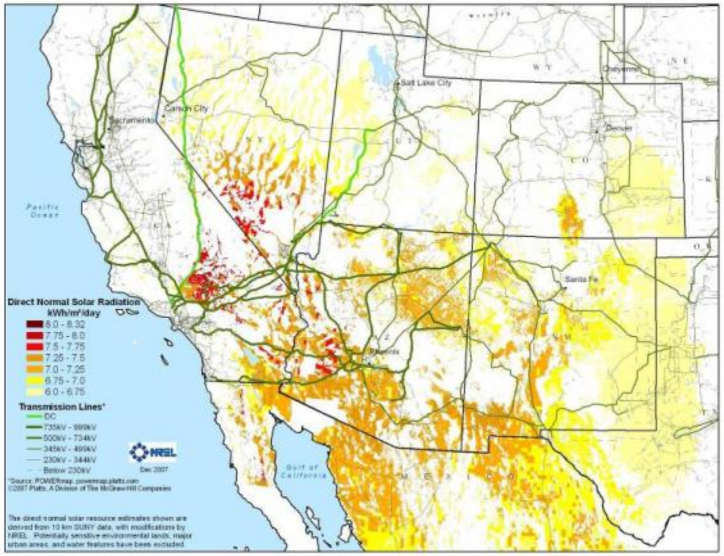
Solar Resource Screening Analysis



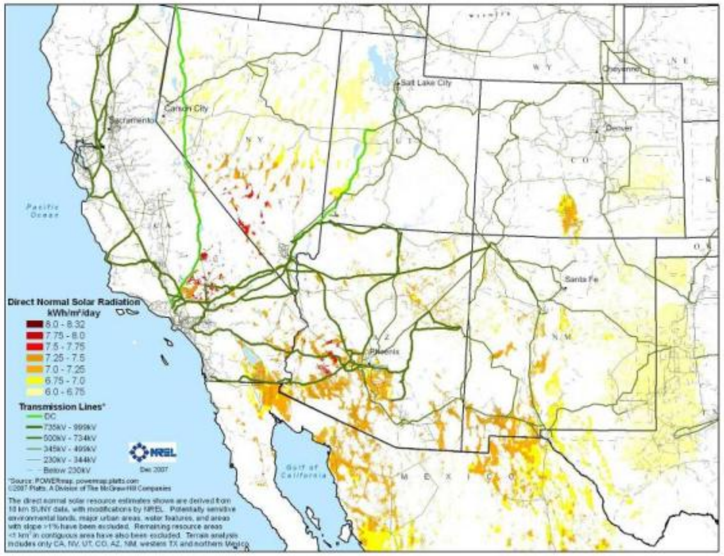
(1) Unfiltered Resource



(2) Solar > 6.0 kWh/m^2-day



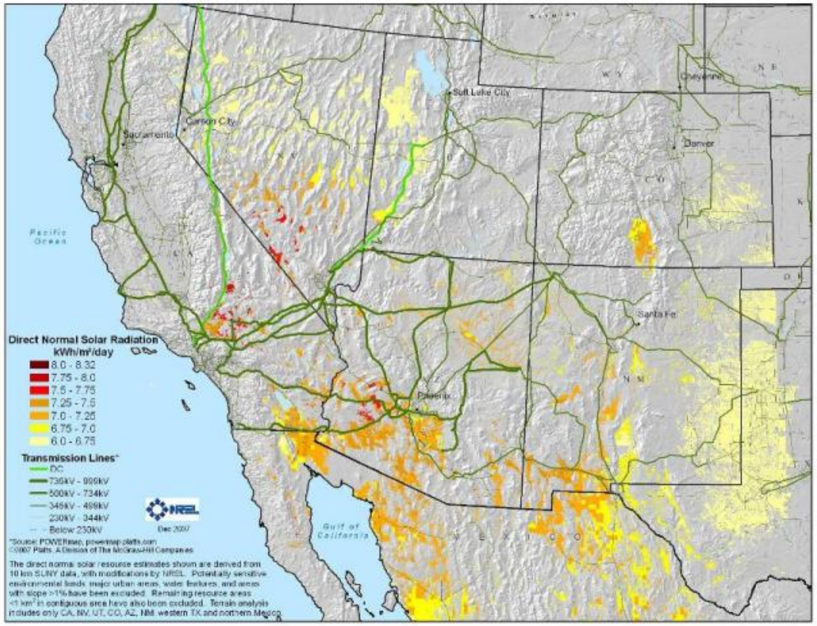
(3) Land-use Exclusions



(4) Slope Exclusions

Raw Utility Solar Resource Potential

State	Land Area (mi²)	Solar Capacity (MW)	Solar Generation Capacity GWh
AZ	13,613	1,742,461	4,121,268
CA	6,278	803,647	1,900,786
CO	6,232	797,758	1,886,858
NV	11,090	1,419,480	3,357,355
NM	20,356	2,605,585	6,162,729
UT	6,374	815,880	1,929,719
TX	23,288	2,980,823	7,050,242
Total	87,232	11,165,633	26,408,956



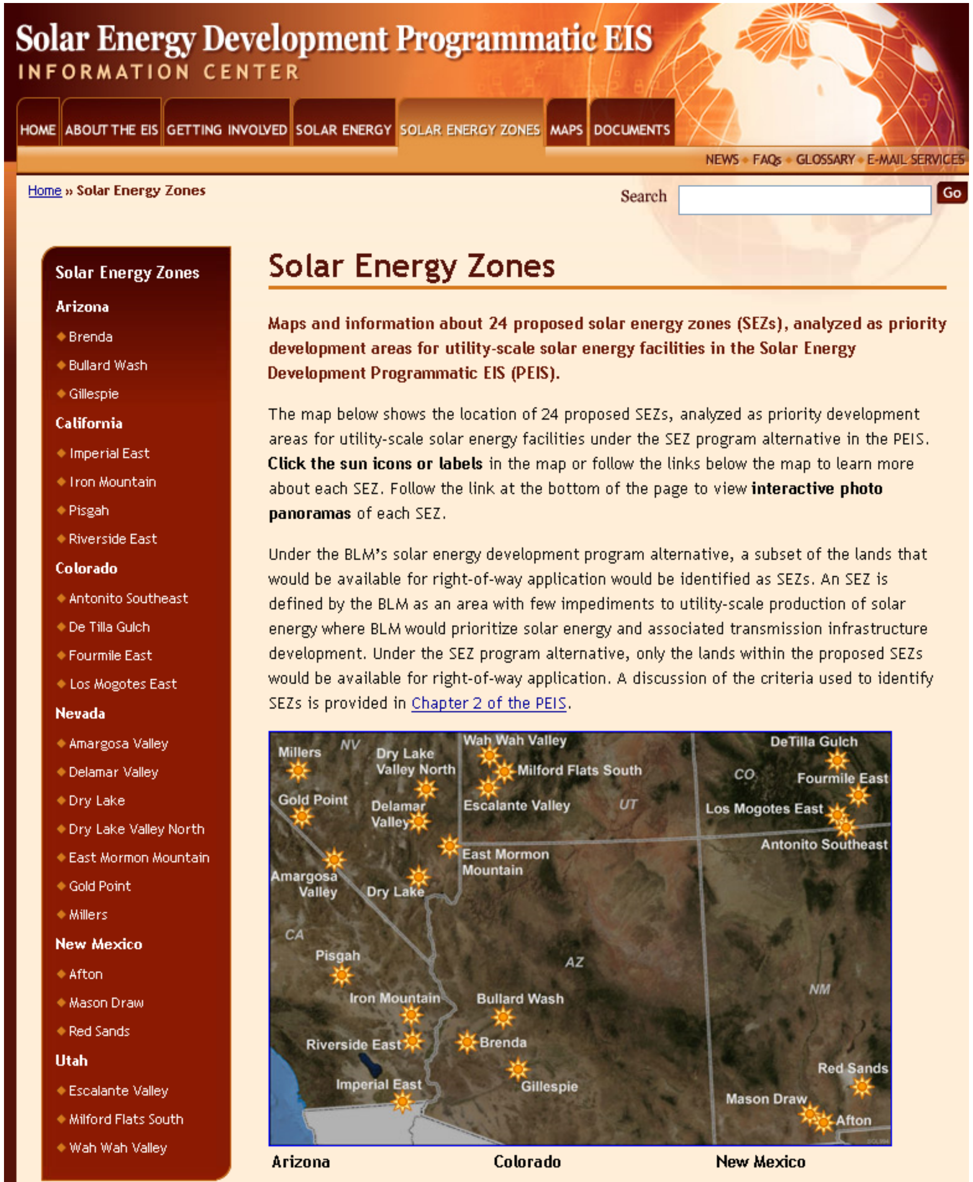
The table and map represent land that has no primary use today, exclude land with slope > 1%, and do not count sensitive lands.
Solar Resource ≥ 6.0 kWh/m²-day
Capacity assumes 5 acres/MW
Generation assumes 27% annual capacity factor

Current U.S. grid:

1,000 GW nameplate capacity

4,000,000 GWh annual generation

Proposed Solar Energy Zones



Solar Energy Development Programmatic EIS
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Solar Energy Zones

Arizona
- Brenda
- Bullard Wash
- Gillespie

California
- Imperial East
- Iron Mountain
- Pisgah
- Riverside East

Colorado
- Antonito Southeast
- De Tilla Gulch
- Fourmile East
- Los Mogotes East

Nevada
- Amargosa Valley
- Delamar Valley
- Dry Lake
- Dry Lake Valley North
- East Mormon Mountain
- Gold Point
- Millers

New Mexico
- Afton
- Mason Draw
- Red Sands

Utah
- Escalante Valley
- Milford Flats South
- Wah Wah Valley

Solar Energy Zones

Maps and information about 24 proposed solar energy zones (SEZs), analyzed as priority development areas for utility-scale solar energy facilities in the Solar Energy Development Programmatic EIS (PEIS).

The map below shows the location of 24 proposed SEZs, analyzed as priority development areas for utility-scale solar energy facilities under the SEZ program alternative in the PEIS. **Click the sun icons or labels** in the map or follow the links below the map to learn more about each SEZ. Follow the link at the bottom of the page to view **interactive photo panoramas** of each SEZ.

Under the BLM's solar energy development program alternative, a subset of the lands that would be available for right-of-way application would be identified as SEZs. An SEZ is defined by the BLM as an area with few impediments to utility-scale production of solar energy where BLM would prioritize solar energy and associated transmission infrastructure development. Under the SEZ program alternative, only the lands within the proposed SEZs would be available for right-of-way application. A discussion of the criteria used to identify SEZs is provided in Chapter 2 of the PEIS.

Arizona Colorado New Mexico

http://solareis.anl.gov/sez/index.cfm

CSP in the US: Operating & Planned

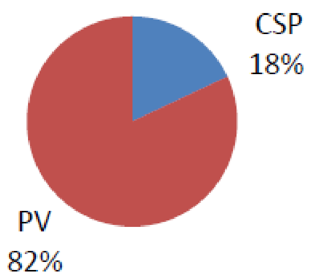
Utility-Scale Solar Projects in the United States
Operating, Under Construction, or Under Development

Updated February 5, 2013

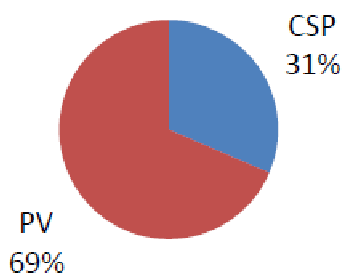
SEIA Solar Energy Industries Association®

Utility-Scale Project Capacity by Technology and Completion Status (MW)				
Technology	Operating	Under Construction	Under Development	Total
CSP	523	1,317	5,244	7,084
PV	2,387	2,870	18,877	24,135
Total	**2,910**	**4,187**	**24,121**	**31,219**

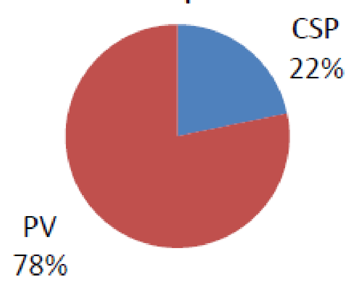
Operating Projects



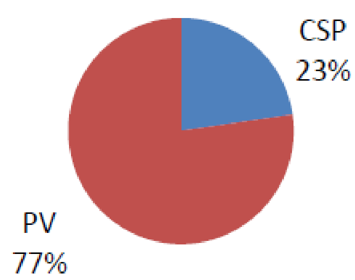
Projects Under Construction



Projects Under Development



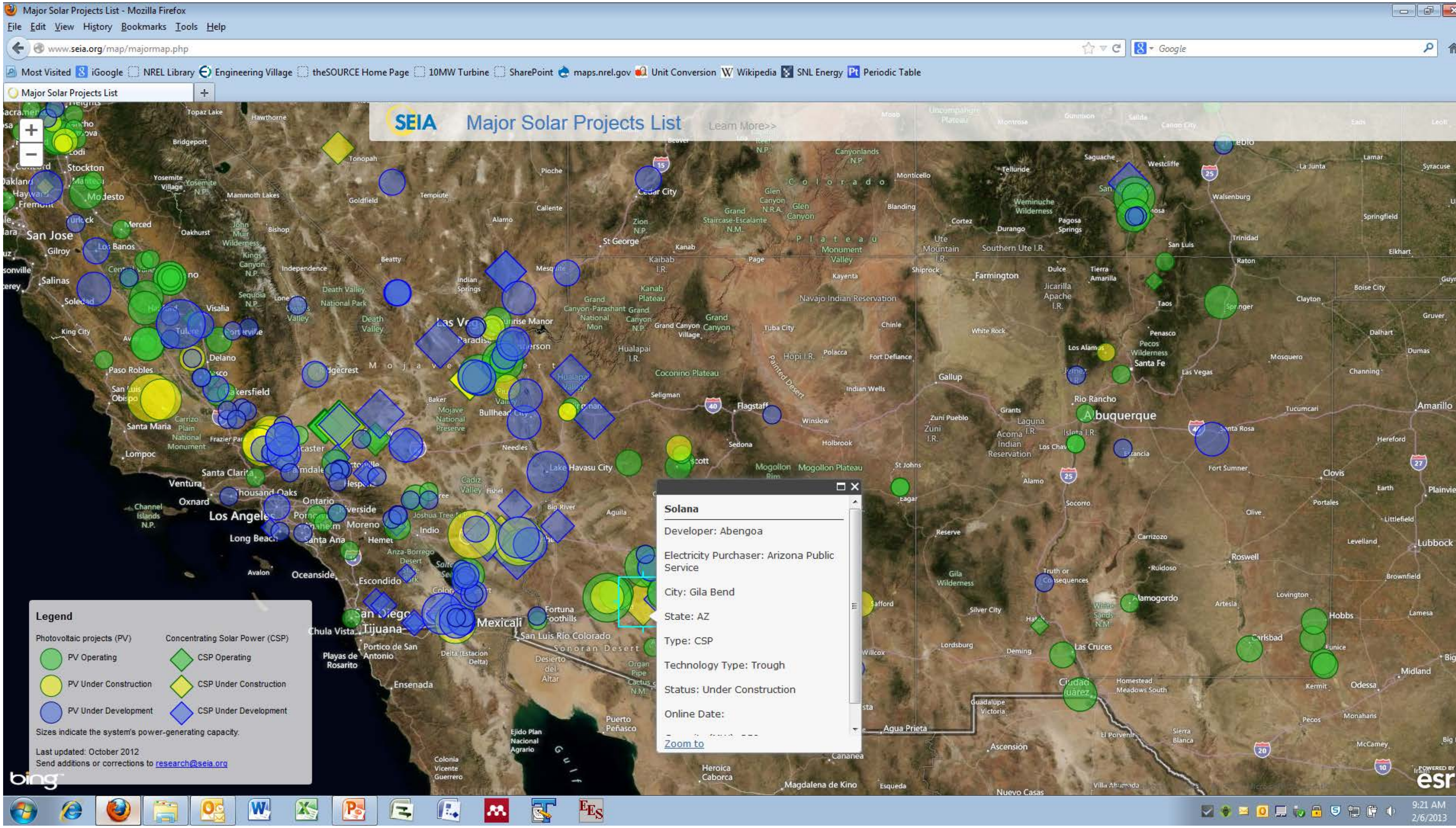
Total Project Pipeline



For projects list go to www.seia.org and http://nreldev.nrel.gov/csp/solarpaces/

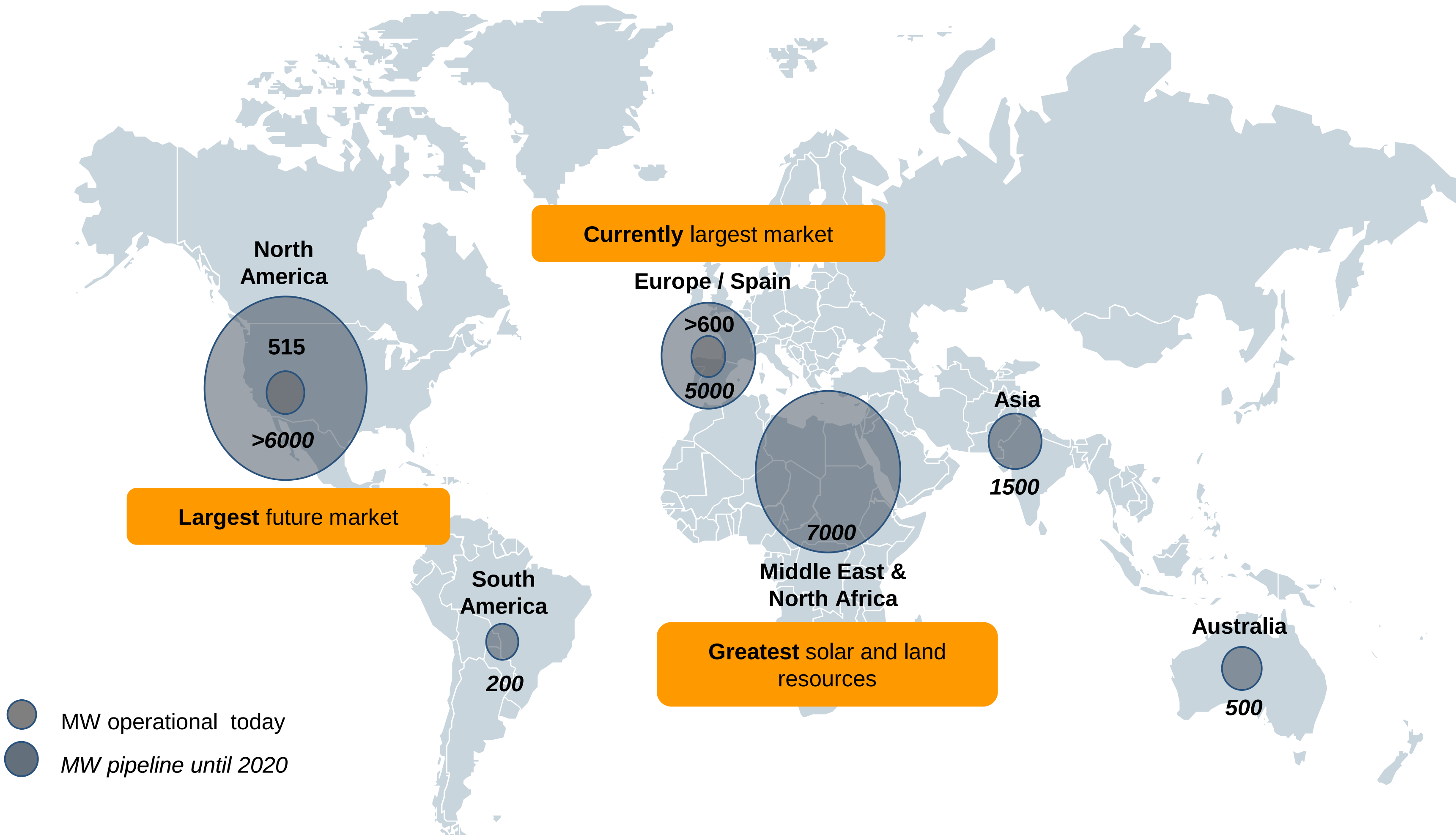
Projects List from SEIA

http://www.seia.org/map/majormap.php



CSP Market Worldwide

Global CSP Pipeline



Discussion

- Technology Overview
  - CSP technologies
  - Hybridization with fossil energy
  - Value of thermal energy storage
  - Water Usage

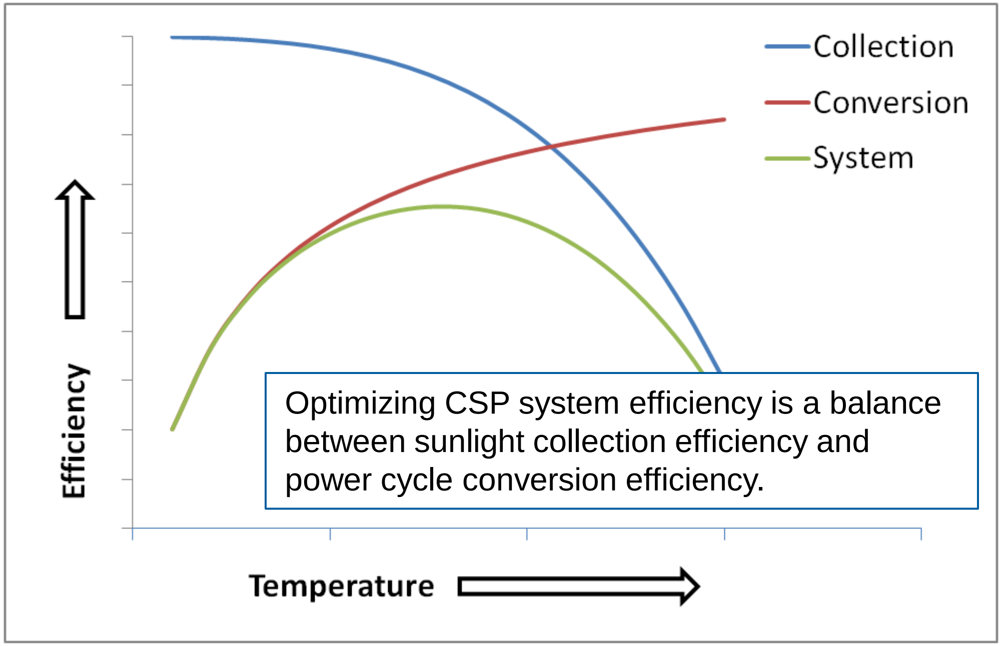
- U.S. and International Market Overview
- CSP Research and Development

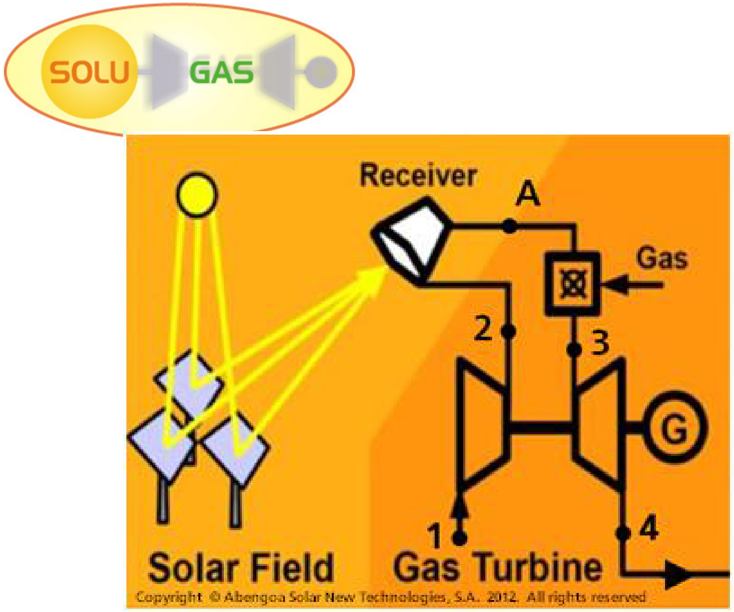
CSP Research & Development

Advanced power cycles:

- Supercritical steam
- Supercritical CO_2
- Air Brayton
- Direct thermal-to-electric

Supercritical CO_2 power skid
(Echogen Power Systems)





CSP Research & Development

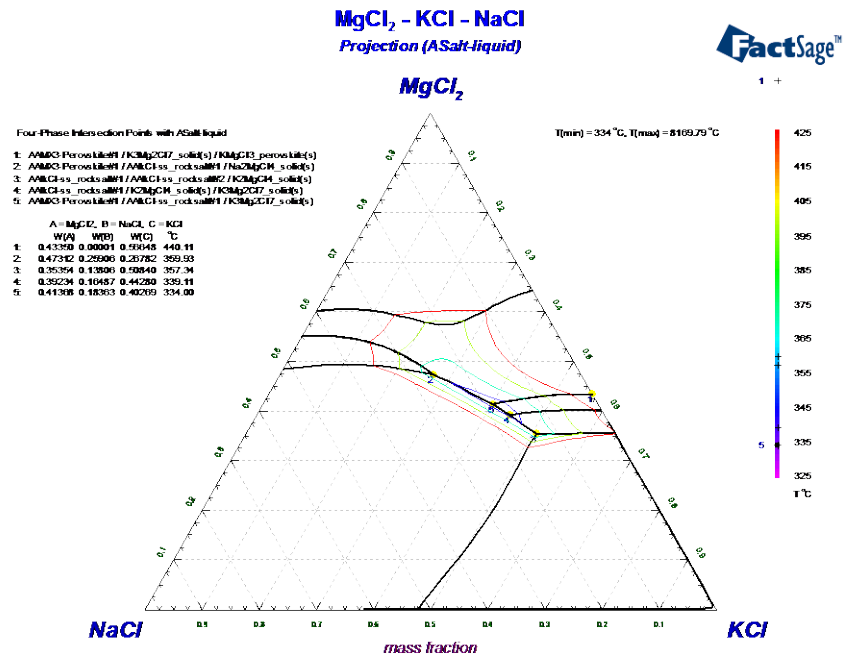
Advanced collector designs:

- Direct steam troughs
- Molten salt troughs
- Linear Fresnel
- Low cost heliostats

CSP Research & Development

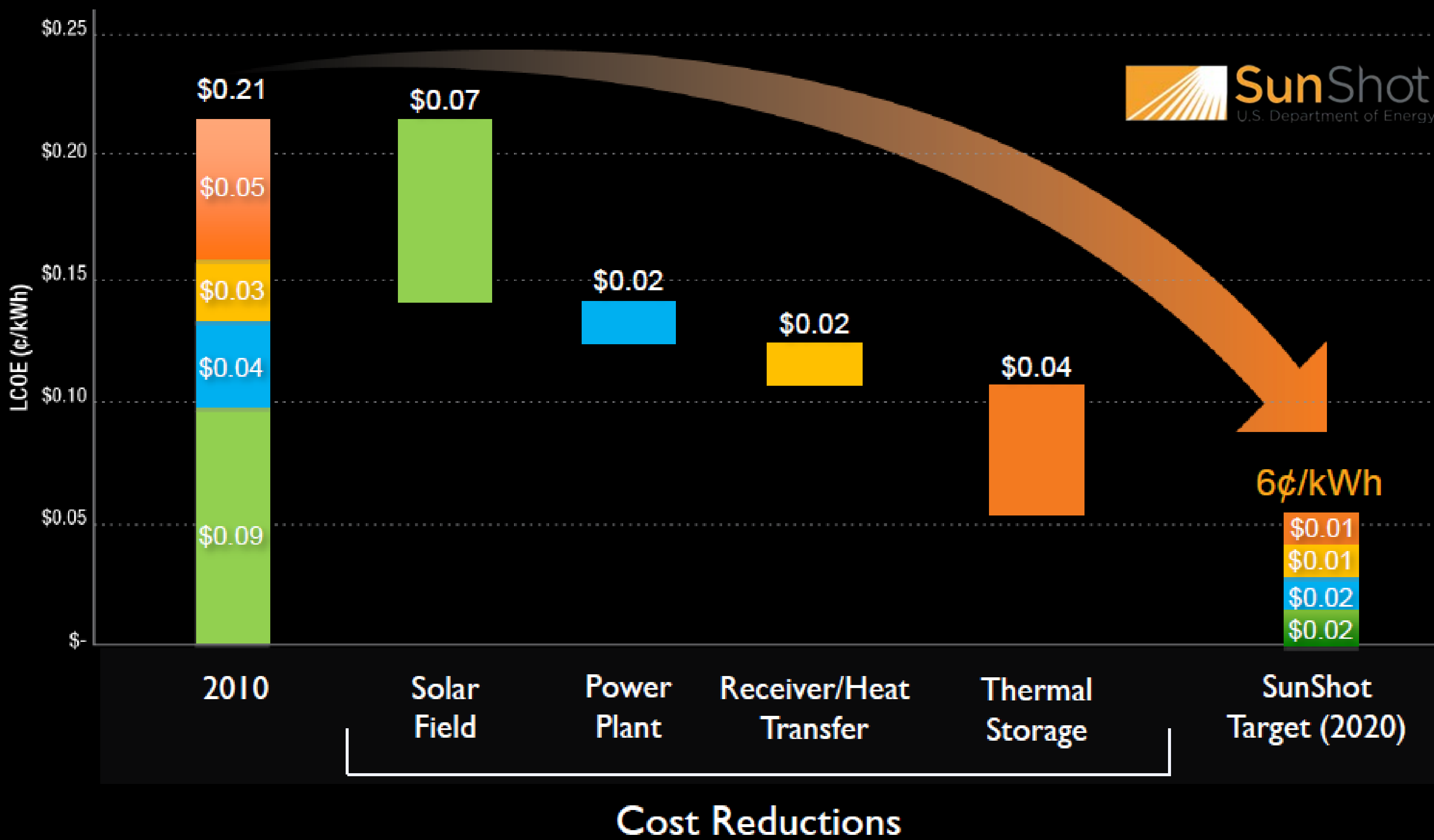
Advanced heat transfer & thermal storage materials

- High-temp salts
- High-temp molten metals
- Phase-change materials
- Thermochemical storage

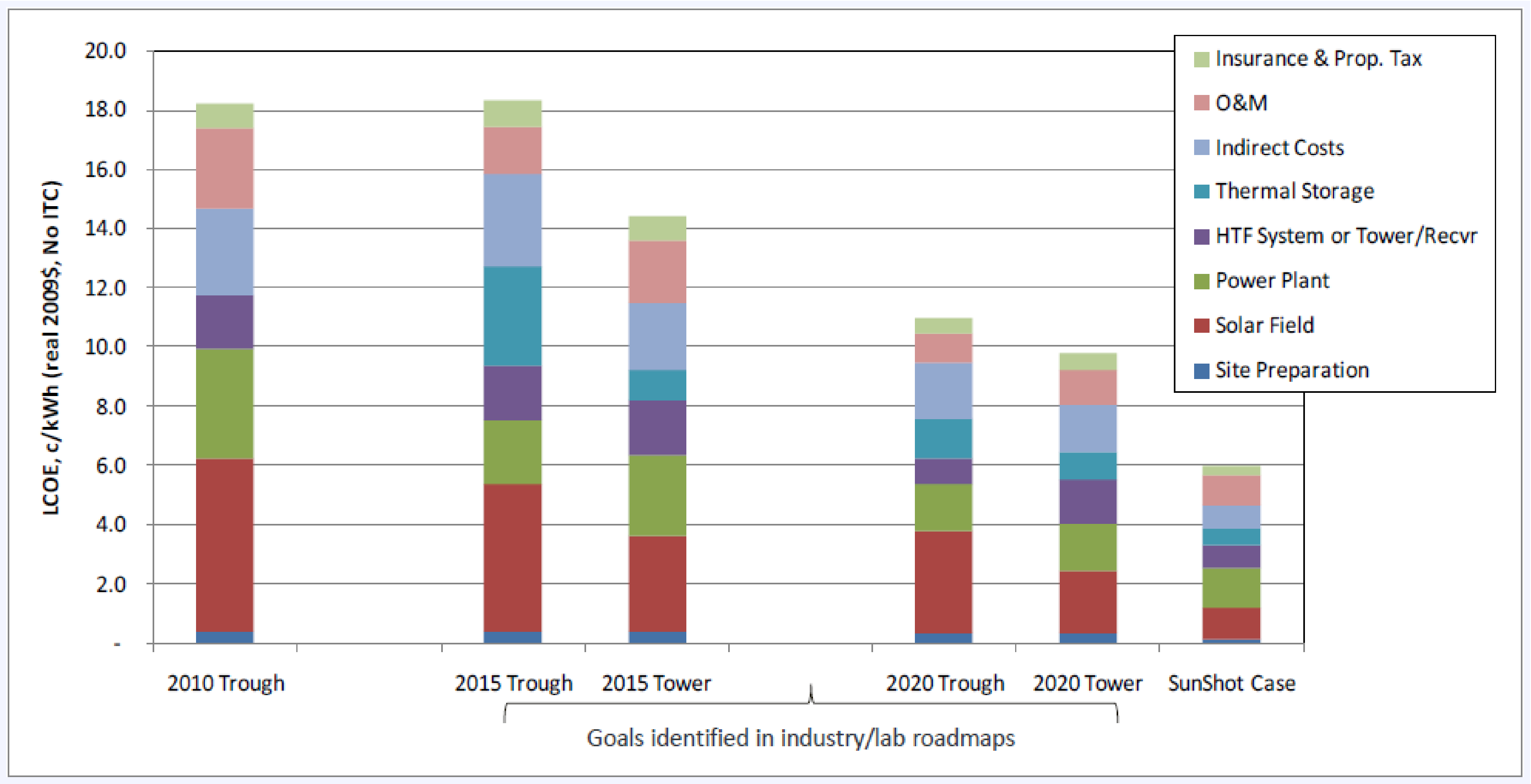



Molten Salt Test Loop, Sandia National Labs

DOE "SunShot" CSP Targets



Estimated CSP Trough and Tower Costs



Assumed location is Daggett, CA

Thank you!

NREL's trough module test facility

For more information:

http://www.nrel.gov/csp/

http://maps.nrel.gov/

http://solareis.anl.gov/

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